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Coastal Benthic Boundary Layer Research Program: A Review of the Third Year

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July 19, 1996

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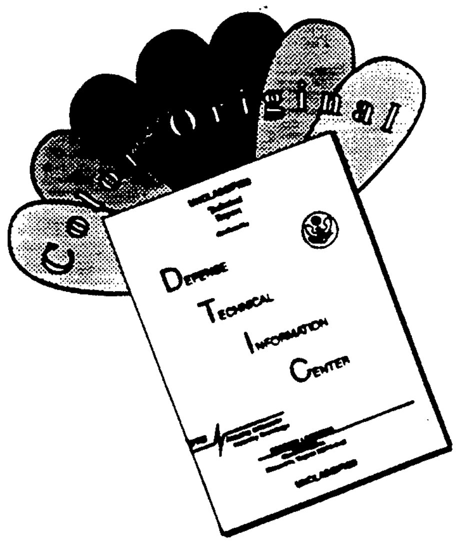

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The Coastal Benthic Boundary Layer (CBBL) Research Program is a 5-year Office of Naval Research study that addresses the physical characterization and modeling of benthic boundary layer processes and the impact of these processes on seafloor structure, properties, and behavior. In this report, results from the third year of the CBBL are summarized. Included are preliminary results from 1995 experiments conducted in carbonate sediments of the Florida Keys (The Key West Campaign). Also included are analyses of data collected during earlier experiments conducted on the soft methane-rich sediments of Eckernförde Bay (Baltic Sea) and on the sandy relict sediments of the northeastern Gulf of Mexico. Year-end reports for the 19 projects supported by the CBBL are included along with a list of publications supported by this program.

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COASTAL BENTHIC BOUNDARY LAYER (CBBL) RESEARCH PROGRAM :

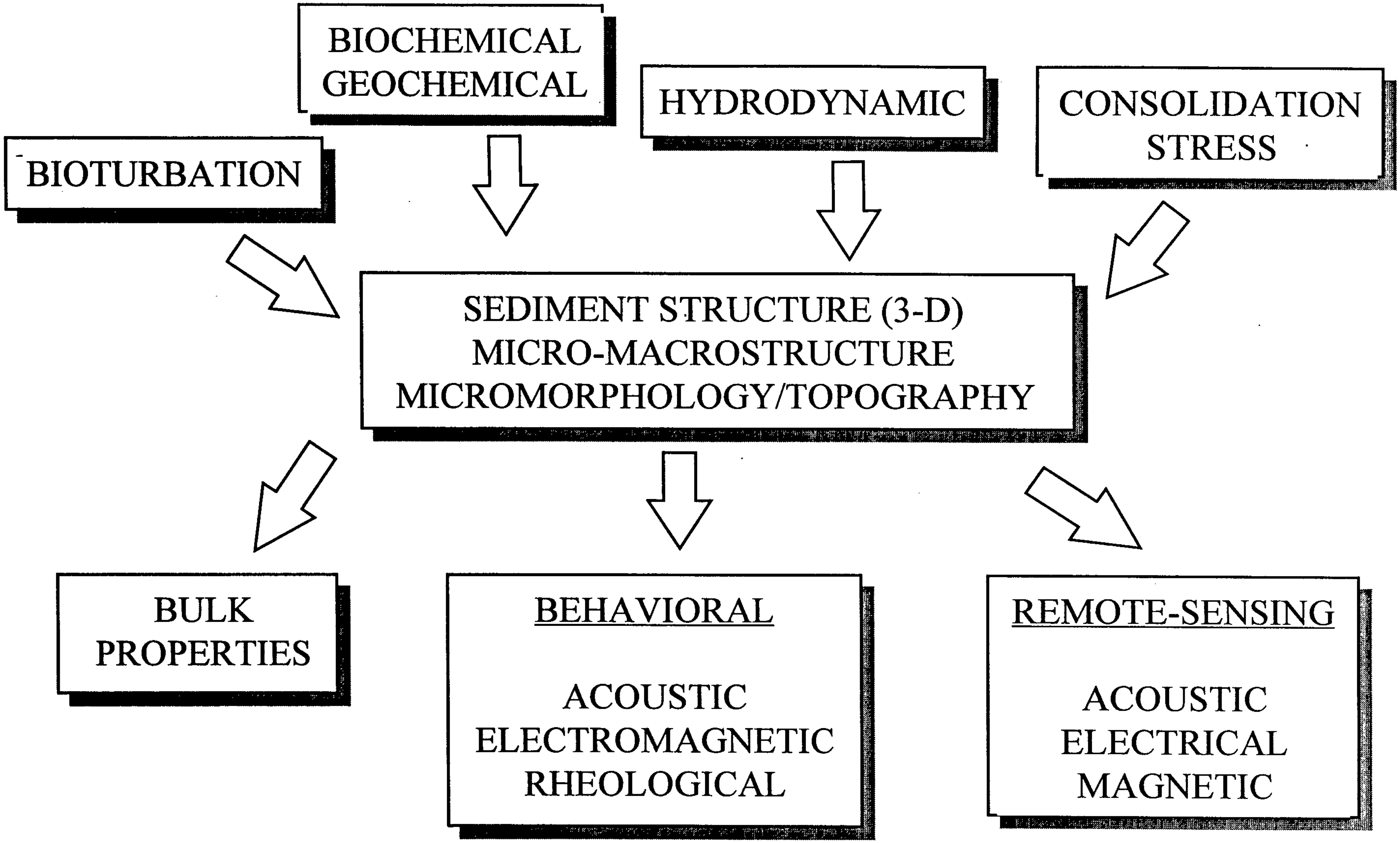
A REVIEW OF THE THIRD YEAR

1.0 INTRODUCTION

The Coastal Benthic Boundary Layer (CBBL) Research Program is a 5-year Office of Naval Research (ONR) program that addresses physical characterization and modeling of benthic boundary layer processes and the impact these processes have on seafloor properties that affect shallow-water naval operations. Four workshops were convened between November 1991 and February 1992 to establish program direction (Richardson, 1992). Based on workshop recommendations, research was focused on modeling the effects benthic boundary layer processes have on sediment structure, properties, and behavior (Figure 1). Sediment physical structure provides the common perspective to: a) quantitatively model relationships among sediment physical, acoustic, electrical, and rheological (mechanical) properties; b) quantify the effects of environmental processes on the spatial and temporal distribution of sediment properties; and c) model sediment behavior (acoustic, electrical, and mechanical) under direct and remote stress.

A basic understanding of the physical relationships among processes and properties will contribute to development of realistic models of: sediment strength, stability, and transport; sediment stress-strain relationships in cohesive and non cohesive sediments; dynamic seabed-structure interactions; animal-sediment interactions; high-frequency acoustic scattering phenomena; and propagation of high-frequency acoustic energy into and through poro-elastic media. Predictive models developed through this program should enhance MCM technological capabilities in several important areas, including: acoustic and magnetic detection, classification, and neutralization of proud and buried mines; shock wave propagation; prediction of mine burial; and sediment classification.

Quantitative physical models are being tested by a series of field experiments at coastal locations where differing environmental processes determine sediment structure (Richardson, 1993, 1994, 1995; Tooma and Richardson, 1995; Richardson and Bryant, in press). The first experiment was a joint United States (Naval Research Laboratory & CBBL) and German (FWG & University of Kiel) study of the gas-rich muds of Eckernförde Bay in the Baltic Sea. At this site biogeochemical processes are responsible for the formation of subsurface methane gas bubbles that significantly affect sediment structure, behavior, and properties. The second experiment was conducted on the West Florida Sand Sheet, southeast of Panama City, Florida. Sediments are a mixture of clastic sands and shells that are reworked by wave-current action (hydrodynamic processes) and biological processes (bioturbation). Joint NRL/FWG experiments were also conducted in a carbonate environment (Florida Keys during February 1995) where bio-


BIOTURBATION
BIOCHEMICAL
GEOCHEMICAL
HYDRODYNAMIC
CONSOLIDATION
STRESS
SEDIMENT STRUCTURE (3-D)
MICRO-MACROSTRUCTURE
MICROMORPHOLOGY/TOPOGRAPHY
BULK
PROPERTIES
BEHAVIORAL
ACOUSTIC
ELECTROMAGNETIC
RHEOLOGICAL
REMOTE-SENSING
ACOUSTIC
ELECTRICAL
MAGNETIC

geochemical diagenetic processes, such as sediment mineralization, dissolution and cementation, control sediment structure. The goal of the CBBL is to provide physical models that predict sediment structure and behavior from knowledge of environmental processes for each environment.

The following sections (1.1 through 1.3) describe CBBL results from the three experimental sites. The descriptions of the Eckernförde Bay and West Florida Sand Sheet experiments are edited from an introductory article from a special issue on GeoMarine Letters (Richardson and Bryant, in press) and the description of the Key West Campaign was edited from the cruise report. References were deleted for this presentation and can be found in the original articles.

1.1 DESCRIPTION OF THE ECKERNFÖRDE BAY EXPERIMENTS

Five joint U.S./German cruises investigating gassy sediments of Eckernförde Bay (Baltic Sea) have been completed. The first cruise, aboard the **WFS PLANET** (1-20 February 1993), was a survey of potential study sites. Sediments were characterized by remote acoustic methods (side-scan, narrow-beam normal-incident, and FM-chirp sonars) and direct sediment sampling with gravity and box cores. A 1.0-by-2.3-km area of uniform sediment was chosen for further study. Sediments at the study site are recently deposited soft muds, with high water contents and very low shear strengths. Remote acoustic measurements suggested methane bubbles were present as shallow as 0.5 to 0.7 m below the sediment-water interface. The existence of gas bubbles in sediments was confirmed by x-ray computed tomography (CT) scans of pressurized core samples.

On the second cruise, also aboard the **WFS Planet** (29 March to 3 April 1993), acoustic and environmental towers were deployed to monitor long-term changes in high-frequency bottom scattering, benthic boundary layer hydrodynamic processes (bed stress from bottom currents), and sediment transport processes (turbidity from photographs and optical backscatterance sensors). Box core samples were collected to characterize benthic community structure, depths and rates of sediment reworking, and sediment properties.

The main experiment (20 April to 5 June 1993) included 80 scientists, engineers and technicians from 18 research organizations. Four German naval research vessels (**HELMSAND, HIEV, KRONSORT, WILHELM PULLWER**) provided extensive platform support. Investigators concentrated on studies of biological processes (bioturbation rates, and benthic community structure), radiochemistry (reworking depths, mixing and accumulation rates), biogeochemical processes (oxygen, sulfur, and methane metabolism), and sediment dynamics (erosion, deposition and transport of sediments). Sediment structure from micron to kilometer scales was characterized and sediment properties including physical, geoacoustic, geophysical and geotechnical properties were quantified both in situ and under controlled laboratory conditions. Porewater and bulk chemical characteristics of sediments were determined. Special attention was focused on the spatial and temporal distribution of the methane layer (acoustic "turbid" zone), including characterization of in situ bubble size and distribution. High-frequency acoustic

scattering and propagation experiments and tests of remote sediment classification (acoustical and electrical) systems were also conducted.

An extensive study of "pockmarks" in Eckernförde Bay was conducted aboard the **WFS PLANET**, on 26-27 October, 1993. In situ measurements of sediment physical properties, CT scans of sediments retained at in situ, sediment chemical characterization, and remote acoustic measurements (sidescan and normal incidence) show sediments with very high porosity (85%), low shear strength (1.14 kPa), and very high (up to 8% by volume) but spatially variable gas contents. The high variability of near-surface acoustic reverberation probably correlates with gas bubble distribution. Preliminary data analysis suggests that fresh water seeps together with methane gas embolism create local pockmarks.

The final CBBL experiment in Eckernförde Bay (27 June to 8 July 1994) included the following: a) continued intercomparison and development of sediment classification techniques; b) more extensive description of in situ sediment structure, gas content, geoacoustic properties, and sediment behavior; c) verification of models to predict acoustic propagation and scattering in gassy sediments; d) geophysical investigations of Kiel Bay using seismic subbottom reflection profiling and a bottom-towed geophysical sled (shear wave velocity and electrical resistivity); and e) continued studies of biological and biogeochemical processes, including the seasonal migration of the methane bubble horizon. A hyperbaric chamber was utilized to measure mechanical and acoustic properties from samples collected and retained at in-situ pressures and to fix samples for TEM microfabric and biogeochemical studies. Results are compared to similar measurements on sediments at in situ laboratory pressure. The size and distribution of methane bubbles were determined at ambient pressure on the aforementioned samples using CT-scan technology. These data are required to test models of acoustic volume scattering from methane bubble populations. Propagation, scattering, and absorption of near-incidence high-frequency acoustic energy, coincident with in situ gradients of sediment geoacoustic properties were measured to test models of acoustic propagation in gassy sediments. Seasonal studies of fine-scale (vertical) rates of bioturbation, sediment accumulation rates, methane oxidation rates, sulfate concentration and reduction rates, and anaerobic methane oxidation rates were continued. Samples were successfully collected for accurate determination of in situ methane concentrations and rates of production. These data should enable the development of a quantitative model that describes the biogeochemical processes controlling distribution and concentration of dissolved and free methane in Eckernförde Bay sediments.

The following describes the experimental environment found at Eckernförde Bay between February 1993 and July 1994 and includes a summary of scientific conclusions from two recent workshops held in Kiel (Wever, 1994) and Eckernförde (Wever, 1995) Germany as well as conclusions from papers in a special issue of GeoMarine Letters (see list of publications at the end of this report). Sediments at the experimental site are soft, silty clays with evidence of considerable biological activity. Sediment organic contents (>5%) are high. The uppermost sediments consisted of a 2-3 cm layer of brown, oxidized mud that overlay a soft, black sediment with a distinct hydrogen-sulfide odor. Surface sediments contained numerous small (100-500 μm long), ovoid fecal pellets produced by the tellinid bivalve *Abra alba*. Radiochemical profiles of

excess ^{234}Th and bioturbation experiments with fluorescence tracer particles demonstrate that most biological mixing is restricted to the top 5-10 mm of the seabed. Sediment accumulation rates, determined by ^{210}Pb geochronology, were approximately 3-10 mm y^{-1}. These surface sediments were heavily colonized by tube-dwelling, surface deposit-feeding spionid polychaetes (*Polydora ciliata*) and surface deposit-feeding bivalves (*Abra alba*). Other polychaetes, bivalves, and crustaceans were present in surficial sediments, some burrowing to 5-10 cm depths. Functional group classification, faunal abundance, organism size, and particle bioturbation experimental results are all consistent with the hypothesis that the benthic community is controlled by regular disturbance that maintains the community at a low level of complexity (i.e., a pioneering community). Ventilation of surface sediment with oxygenated bottom water by the small, head-down, deposit-feeding *Capitella* sp. polychaetes and tubificid oligochaetes probably controls the depth of the brown, oxidized layer and affects rates of near-surface biochemical processes. Laminated bedding, preserved in the sedimentary record, results from alternating deposition of storm-suspended sediments (non-pelletal, often graded bedding) from adjacent shallow-water areas and a fair-weather deposition of organic-rich suspended material (anisotropic pelletal fabric). This record is preserved as a result of relatively high sediment accumulation rates in a predominantly depositional environment and the absence of significant biological mixing.

High sedimentation rates, near-surface anoxic conditions, and restricted biological activity result in surficial sediments (0-30 cm bsf) with very low in situ values of shear strength (0.2-1.6 kPa), compressional wave velocity (1423-1434 m s^{-1}) and attenuation (0.3-4.2 dB m^{-1} at 58 kHz), shear wave velocity (7-9 m s^{-1}), and shear modulus (3×10^5 N m^{-2}) . Values of sediment water content and porosity decreased rapidly in the upper 10 cm from over 500% (93% porosity) to 266% (87% porosity) at 40 cm, whereas values of sediment bulk density (1.13 to 1.23 g cm^{-3}) and laboratory-measured shear strength (0.30 to 1.28 kPa) increased over the same depth interval. Both the values and variability of surficial geoacoustic properties at these centimeter scales were low compared to previous studies of fine-grained sediments.

In addition to standard laboratory methods, sediment macrostructure was measured by x-radiographic and micro-resistivity imaging of sediment cores. Graded and laminated bedding, as well as the burrows and occasional shells, were evident in x-radiographs of upper 30 cm of surface sediments. X-ray-computed tomography (CT) analysis of sediment cores indicate that feeding pockets and laminae are the primary source of marcostructural and physical property variability. Microresistivity imaging of these sediments shows fine scale (mm) variability in sediment electrical conductivity that translates into greater resolution and higher variability than determined by standard laboratory techniques. Image-based texture analysis of x-radiographs of near-surface sediments indicate that density structure is highly anisotropic with shorter correlation lengths in the vertical (graded or laminated bedding) than the horizontal direction.

Sediment microstructure, in the upper 2 m of the sediment column, is characterized by dense aggregates of silt and clay-sized particles separated by relatively large, fluid-filled canals. This pattern may be a remnant of a surficial zone pelletized by deposit-feeding invertebrates. High sediment permeability (10^{-4} - 10^{-6} cm s^{-1}) for muds is probably related to the very loose sediment microstructure. Weak sediment fabric may also explain high values of sediment compressibility;

whereas, physico-chemical strengthening of interparticle bonding may account for the high apparent over consolidation of near-surface Eckernförde mud.

CT scans of pressurized core samples reveal only occasional methane gas bubbles from 20 to 100 cm depth while below a meter, numerous clusters of small methane bubbles are found . These bubbles occur in distinct horizons rather than in a continuous distribution. Gas bubble concentrations ranged from 0 to 2% by volume within the main experimental site and as high as 8% on the seafloor within a nearby pockmark. Larger gas bubbles were not spherical but had two long and one short axes (disk-shaped). The acoustically turbid layer (i.e., the top of the gas bubble layer) migrates with season, occurring nearer the sediment-water interface during fall and winter months and deeper in the sediment during the spring and summer. It is postulated that fresh water percolation (pore fluid salinity) and seasonal changes in bottom water temperature affect the depth of the acoustic turbid zone by controlling rates of biochemical reactions and methane solubility. In situ measurements of sediment geoacoustic properties show zones of highly attenuated compressional waves 50-150 cm below the sediment-water interface. The depth distribution of these zones corresponds to gas bubble distributions, and attenuation is probably a result of scattering from methane bubbles. Shear waves appear unaffected by the presence of methane bubbles down to depths of 2 m.

Biogeochemical studies demonstrated that methane concentrations in this organic-rich, anoxic sediment reach saturation within less than a meter of the sediment-water interface. This gas-charged horizon migrates vertically and alters its areal distribution with season. Aerobic metabolism is generally restricted to the upper 1-2 cm of sediment with sulfate reducing sediments (50-100 cm thick) found between the zones of aerobic respiration and methane production. Rates of microbial processes (anaerobic sulfate and methane reduction; methane production), pore water salinity profiles, and stable isotopic characterization of methane and dissolved organic carbon are used to model the concentrations and fluxes of methane within the upper 2 m of the sediment column.

A unique set of time-series data on bottom currents, pressure, temperature, turbidity, and acoustic backscattering was collected. Spectral analysis of bottom current and pressure data identified oscillations correlated with semidiurnal tides and a Baltic-wide seiche . It is postulated that the relatively weak barotropic currents, driven by the Baltic-wide seiche, generate local, near-resonant internal waves within Eckernförde Bay which, in turn, generate the stronger baroclinic currents that were observed. During the deployment, neither wind-generated waves or baroclinic currents generated bottom stresses sufficient to erode sediments. However, bottom stress was sufficient to advect sediment flocs eroded from shallower waters thus clouding bottom waters with suspended material. This erosional event changed bottom characteristics as well as benthic animal communities and also corresponded with changes in acoustic scattering. Analysis of high-frequency acoustic backscattering data demonstrated that scattering originates from a layer of free methane gas rather than the sediment-water interface. Spatial and temporal variability, including migrations and concentrations, of free methane gas probably account for the spatial variability (meter scale) and temporal decorrelation (day scale) of backscatter images. The relationship between hydrodynamic conditions (changes in bottom current velocity, bottom temperature, turbidity, and hydrostatic pressure) and acoustic scattering is presently unknown.

Over 1200 km of acoustic profiling were completed during the Eckernförde experiments. These data were used not only to select a uniform experimental site but to provide accurate bottom and/or subbottom characterization of sediment physical and geotechnical properties over the wide variety of sediment types (gassy and nongassy muds, muddy sands, sands and glacial tills) found in Eckernförde and Kiel Bays. Of particular importance, is correlation of large-scale seismic and/or lithological variability with both present-day environmental processes (e.g., distribution of acoustic turbidity) and the depositional and diagenetic history of sediments of the Western Baltic Sea. The acoustic data, combined with sediment physical property data, will also be used to improve or develop new techniques for remote sediment classification.

1.2 DESCRIPTION OF THE WEST FLORIDA SAND SHEET EXPERIMENT

The West Florida Sand Sheet experimental site is located 23 nmi southwest of Panama City, Florida on an otherwise fine-grained, sand-wave field (Cape San Blas Sand Facies) of the inner continental shelf. The shelf of the northeastern Gulf of Mexico is currently sediment-starved with most material deposited by the Apalachicola River during lower sea stands. Recent large-scale seafloor morphology is controlled by hydrodynamic processes, especially major storms. Silt- and clay-sized particles are occasionally deposited over the sand sheet during severe storms. These finer sediments can be either worked into the predominantly sandy surface sediments by biological activity or winnowed out of the sediments by minor storms. Small ripples form at the coarse sand site in response to the passage of winter fronts, and may persist for months. Hurricanes and other major storms also change bottom relief forming 2-10 m megaripples as a result of strong bottom currents. Megaripples formed after the passage of Hurricanes Elena (September-October 1985) and Kate (November 1985) decayed after two years, presumably a result of active bioturbation during quiescent periods.

Acoustic surveys of a 20-km^2 area, using sidescan sonar, chirp sonar and 3.5-kHz echo sounding, allowed experimenters to delineate a 600 by 625-m primary experimental site which had uniformly high acoustic reflectivity. Sediments in this highly reflective area were coarse-grained sands (mean phi: 0.84ϕ) mixed with shell hash, coralline algae fragments and numerous large mollusk shells. Sediments outside the experimental site were comprised of lower reflective, fine-grained sands (mean: 2.39ϕ) with little shell hash and occasional muddy layers or inclusions. Values of porosity (mean: 40.3%), density (mean: 2.01 g-cm^{-3}), compressional wave velocity (mean: 1711 m s^{-1}), attenuation (mean: 30.4 dB m^{-1} at 58 kHz) and shear wave velocity (mean: 118 m s^{-1}) varied little between sediment types. CT-scans of sediment core samples from the highly reflective area reveal thousands of shell and shell fragments per cubic meter.

Acoustic boundary scattering experiments and time-lapse monitoring of environmental conditions were restricted to the highly reflective sediment. Temporal decorrelation of successive acoustic scans of the seafloor was an order of magnitude greater than at the Eckernförde site. Correlation of acoustic scans collected during experimental manipulations of the bottom by

divers suggests that the large acoustic decorrelation results from changes in fine-scale topography. The near-bed hydrodynamic regime was dominated by reversing tidal currents with typical speeds of 10 cm s^{-1} or less. Maximum bed shear stresses remained too low to resuspend or transport the sediments. The high temporal variability in acoustic scattering strengths must, therefore, be related to biologically induced changes in bottom micro-roughness. Therefore, kilometer-scale, decadal sediment characteristics of this site are dominated by hydrodynamic processes, especially major storms, whereas meter-scale, seasonal-to-daily bottom characteristics are controlled by minor storms and biological activity

1.3 DESCRIPTION OF THE KEY WEST CAMPAIGN

During February 1995, a four ship (WFS PLANET, R/V SEWARD JOHNSON, R/V PELICAN & R/V SEAWARD EXPLORER), over 100 scientist, scientific campaign was mounted in waters of the western Florida Keys. Experiments were conducted under permits issued by the U.S. Park Service and the National Oceanographic and Atmospheric Administration (NOAA). Scientific experiments were focused on the carbonate sedimentary environments in the vicinity of the Marquesas Keys and the Dry Tortugas.

Experiments that made up the Key West Campaign were supported by numerous programs that crossed the barriers of applied and basic research. Central to the experiments was ONR's Coastal Benthic Boundary Layer program. This basic research program is directed towards the physical characterization and modeling of benthic boundary layer processes and the impact that these processes have on seafloor properties that affect shallow-water naval operations. Of particular interest during the Key West Campaign, was the effects of biogeochemical processes (mineralization, cementation and dissolution) on surficial sediment diagenesis. The CBBL experiments provide a unique opportunity for more applied programs to address issues such as mine burial, sediment classification technology, and high-frequency bottom-interacting acoustics in a well-understood and characterized environment.

The Technical Cooperation Program (TTCP: Samuel Tooma, coordinator) took advantage of this well-classified sedimentary environment and the infrastructure provided by the CBBL to access and test the current state of technology for acoustic remote classification of sediments. The following 8 systems were tested: ROXANN (UK); Datasonics first generation Chirp Seafloor Classification System (UK); ISAH-S Bottom Classification System (Canada); Sediment Density Profiling System (New Zealand); High Resolution Acoustic Seafloor Classification System (US); Full Spectrum Chirp Sonar (US); Multichannel Seismic profiler (UK); and the Quantitative Side Scan Sonar (Germany). Co-located measurements were made over a variety of sediment types (muds, loose and hard packed sands, coral rubble and live reefs). In addition to these 8 systems the New Zealand Electronic Sediment Strength Probe was used to provide point strength measurements. Sediment strength is an important input to the impact mine burial model. Most other ground truth data collection was supported by the CBBL and the University of South Florida Unmanned Underwater Vehicle (UUV) Remote Sensor Program.

The Key West Campaign also provided a unique opportunity to demonstrate the MCM Tactical Environmental Data System (MTEDS) (Samuel Tooma and Dan Lott coordinators). The MTEDS program is designed to demonstrate an organic capability for MCM ships to make environmental measurements that include necessary inputs into performance prediction models and/or real-time tactical decision aids. The potential for remote characterization of sediment engineering properties was studied by a joint program among NRL, Naval Facilities Engineering Service Center (NFESC) and Defense Science Establishment (DSE) of New Zealand. NFESC measured in situ strength related engineering properties using either a piezocone tripod (penetration resistance and pore pressures) or expendable doppler penetrometer (shear strength). Continuous profiles of sediment density were measured with the New Zealand broadband sediment density profiling system and point measurements of sediment penetration resistance were made with the New Zealand Electronic Sediment Strength Probe. Measured engineering properties will be compared to predictions generated by the NRL High Resolution Acoustic Seafloor Classification System (HR ASCS) .

The cooperative program among the University of South Florida (USF), Florida Atlantic University (FAU), and NRL "Sediment Characteristics of Selected Coastal Environments" used the opportunity to collected data to develop and improve inversion techniques for normal incidence sediment classification systems which are used to remotely determine sediment physical and geoacoustic properties. The goal of this project is to determine mechanisms responsible for scattering of high frequency acoustic energy. The sediment classification system will ultimately be a part of the Unmanned Underwater Vehicle being developed by USF for naval MCM operations.

The Joint High-Frequency Backscattering Experiments (JOBEX) program, supported by FWG, included measurements of backscattering strengths using a 100 kHz quantitative side-scan sonar. These data were used not only to select the main Key West Campaign study site but to provide much needed quantitative measurements of acoustic bottomscattering from a variety of carbonate sediment types. Experiments were also performed to study long- and short-term mine burial in carbonate sediments. Self-recording mines were deployed at a variety of sediment types (determined from records of the side-scan sonar with 3.5 kHz subbottom profiler) near the Dry Tortugas. Long-term burial processes were studied in the Dry Tortugas (scour burial) and near Rebecca Shoals (sand ridge migration).

High-frequency acoustic scattering measurements were supported by the CBBL, MTEDS, APL/PSU Torpedo Environments, and ONR Acoustic programs, as well as by the Defense Research Agency (DRA) of the UK. Measurements were made from the SEAWARD EXPLORER using the APL/UW BAMS tower (@ 40 & 300 kHz) and two broadband transmitter/receiver arrays provided by DRA (30-210 kHz); from the PLANET using the German quantitative side scan sonar (100 kHz); and from the SEWARD JOHNSON using a remotely operated vehicle (ROV) designed by ARL/UT (200 kHz). Scattering data (forward, back and out-of-plane) were collected from both the air-water and sediment-water interfaces over the range of frequencies commonly used by MCM forces. The abundant seafloor and water column environmental data collected during the duration of the acoustic experiments will be used to

improve understanding of scattering mechanisms and to validate or develop new acoustic scattering models.

The campaign was highly successful with over 1300 nmi of acoustic lines, nearly 500 core and grab samples. and 100 man-hours diving. The following list provides an indication of the extensive sampling conducted during the Key West Campaign.

1. Over 350 hours of acoustic profiling was completed during the Key West Campaign from the R/V SEWARD JOHNSON, R/V PELICAN & WFS PLANET. Acoustic sediment classification systems included the High Resolution Seafloor Classification System (HR ASCS) (using 3.5, 12, 15, 40, & 50 kHz transducers); ROXANN (28 & 200 kHz); ISAH-S (28 & 200 kHz); the Datasonics Chirp Sonar (1.0 - 10 kHz); the Full Spectrum Chirp Sonar (1.5 to 15 kHz); the Klein quantitative side scan sonar (100 & 500 kHz); and the Sediment Density Profiler (1 - 15 kHz). In many cases systems were run simultaneously. A square area (5 km x 5 km) southeast of the Dry Tortugas was extensively surveyed using the FWG 100 kHz side-scan sonar with a 3.5 kHz subbottom profiler along with the NRL Acoustic Sediment Classification System. The side scan, subbottom, and ASCS acoustic data sets were used to construct a map of surface sediment character and depth of the sediment pond within the primary CBBL study area. This map was used to select a uniform area for the main experiment and to provide a guide and extensive ground truth for sediment classification trials. Over 1300 nmi of acoustic tracks were run with all or at least most acoustic systems in the Dry Tortugas test area and areas north of the Marquesas Keys and near Rebecca Shoals. Extensive ground truth data (see # 3, below) is available to calibrate and compare results from these acoustic systems.

2. Box core samples (208) were collected for radiological, geotechnical, biological, biogeochemical, physical and geoacoustic studies. These data will provide: (1) an understanding of how these environmental processes affect sediment structure; (2) a quantification of sediment structure from the micron to cm scales and; and (3) a measure of sediment behavior under various stress-strain conditions.

3. Sediment ground truth was collected with 155 gravity cores, 11 vibracores, and 28 grab samples. Most of these cores were x-rayed and logged at a shore-based laboratory provided by the Key West Naval Air Station. Sediment geoacoustic, physical, and geotechnical properties were either determined during the campaign or will be later measured at investigators' facilities.

4 Divers made 82 dives to deploy in situ probes, collect cores, take still and video camera pictures of the bottom characteristics, measure roughness and mine burial, and conduct seafloor experiments where the bottom roughness or structure was manipulated. Observations of bottom characteristics, bottom roughness, and mine burial were made with diver-operated still and video cameras and by surface-operated cameras on over 50 occasions. Divers also collected 66 cores for sediment physical, geoacoustic, and biogeochemical characterization.

5. In situ geoacoustic and geotechnical probes (Acoustic Lance, Expendable Doppler Penetrometer, Piezocone, Sediment Strength Probe, ISSAMS, GISSAMS, Neptune, DIAS, diver vanes & piezometer) were deployed on 131 occasions.

6. Temporal bottom scattering measurements were made from the R/V SEAWARD EXPLORER using the APL Benthic Acoustic Measurement System (BAMS), an autonomous bottom-mounted tripod. The circularly scanning 40 kHz and 300 kHz sonars have angular resolutions of 5° and 1°, respectively within the 50 m radius scan. Data scans are presented as scattering strengths (Lambert parameter). Correlation of successive images shows changes in acoustic backscattering which can be related to the effects of environmental processes on sediment structure. A total of 488 scans were made with the 40 kHz sonar, and 45 scans were completed with the 300 kHz sonar. Areas of rapid and slow decorrelation were investigated by divers, and experiments that included changes in bottom roughness were conducted within the acoustic field of view. Bistatic scattering measurements were made using the BAMS 40 kHz sonar as a source and a steerable 1.5 m array as a receiver. Backscattering and target strength measurements were also made by DRA using sterile transmitter/receiver arrays covering the 30 to 210 kHz frequency range. At nine sites within the Dry Tortuous grid, ARL/UT conducted 200 kHz bottom backscatter measurements over a variety of grazing angles. Two sets of backscatter measurements were made in the vicinity of the APL/UW BAMS acoustic tower experiments. The spatial distribution of bottom backscattering was also measured using Fag's quantitative side-scan sonar (100 kHz). A bottom-mounted acoustic reflector was deployed for calibration of the side-scan sonar data.

7. Mine burial (impact, scour and sand ridge migration) experiments were conducted from the WFS PLANET and the R/V SEAWARD EXPLORER. Fourteen short-term impact burial trials were made using the FWG self-registration mines, and long-term scour burial studies were conducted with six mines either within or near the acoustic field of view of the BAMS tower. Mines within the BAMS field of view (MK 42, MK 82, MK 52, German self-registration and Manta) were also subjected to target scattering studies. Attempts were made to correlate reverberation statistics with scour around the mines. Divers made numerous visual and photographic observations in an effort to document mine scour. Two FWG's self-registration mines were also deployed near Rebecca Shoals for studying mine burial by sand ridge migration.

8. Water column measurements included wave rider buoys, Seabird and General Oceanics CTDs, the Chelsea AquaShuttle, and an RDI Acoustic Doppler Current Profiler. These data were collected in support of both the MTEDS tests and acoustic backscattering experiments.

9. An instrumented tetrapod was deployed successfully by the Virginia Institute of Marine Science (VIMS) near the Dry Tortugas for 21 days. Hourly measurements were made of bottom water current velocity (Marsh-McBirney electromagnetic current meters), turbidity (optical backscatterance sensors), bottom roughness (digital sonar altimeter), temperature (digital thermistor), and sea level (digiquartz pressure sensor). The purpose of these measurements is to characterize the physical processes responsible for sediment erosion, transport and deposition.

10. In meeting the MTEDS objectives given in the previous section, 27 track lines covering 108 nmi were run within the Dry Tortugus grid area. During these runs, the following data was collected in situ, stored in the MTEDS data base, displayed on the workstation's screen, and used to make such predictions as percent mine burial: (1) bathymetry; (2) current velocities collected

with an Acoustic Doppler Current Profiler; (3) sediment classification data from the ship's fathometer and NRL's High Resolution Acoustic Seafloor Classification System; and (4) differential GPS navigation. In addition, the following recorded data sets were re-played into the MTEDS data base: (1) high-frequency acoustic reverberation data collected with an SQQ-32 mine-hunting sonar; (2) sound speed profile data computed from conductivity, temperature and depth collected with the AquaShuttle excursion device; and (3) conductivity, temperature, and depth data collected with a CTD. Results from this demonstration have essentially proven the MTEDS concept.

11. NFESC measured in situ strength related engineering properties at 42 locations using either a piezocone tripod (penetration resistance and pore pressures) or expendable doppler penetrometer (shear strength). Measurements with the New Zealand sediment density profiling system (1 - 15 kHz) were made along 27 lines (97 nmi) and with the New Zealand Electronic Sediment Strength Probe at 22 sites (110 measurements). Measured engineering properties will be compared to predictions generated by the NRL High Resolution Acoustic Seafloor Classification System.

1.4 PUBLICATION PLANS

Preliminary results of the Eckernförde Bay experiments were presented at the AGU/ASLO "Ocean Sciences" meeting held in San Diego, CA (21-25 February, 1994) and at the Acoustical Society of America meeting held in Austin, TX (28 November- 2 December, 1994). Proceedings of a workshop "Gassy Mud Workshop" held at FWG in Kiel, Germany (11-12 July 1994) and the workshop "Modelling Gassy Sediments of Eckernförde Bay" held in Eckernförde, Germany (26-30 June, 1995) were published by FWG (Wever, 1994 and 1995). Twenty papers in a special issue of GeoMarine Letters, devoted to Eckernförde Bay and West Florida Sand Sheet experiments are in press. Results from the Key West Campaign were presented at the SEPM conference held at St. Petersburg, Florida (14-16, August 1995) and will be part of a special issue of GeoMarine Letters scheduled for publication in 1996. A special issue of Continental Shelf Research is also planned for the Eckernförde Bay experiments. A list of publications from CBBL experiments is found in section 3.0 of this report.

1.5 ACKNOWLEDGMENTS:

Operational support for the Eckernförde Bay experiments was provided by FWG, WTD-71, and University of Kiel and by Texas A&M University for the West Florida Sand Sheet experiments. Support for the Key West Campaign was provided by the Key West Naval Air Station; US Park Service, Fort Jefferson National Monument and South Florida Regional Resources Center of the Everglades National Park; US Coast Guard Aids to Navigation Team; and National Oceanic and Atmospheric Administration, Florida Keys National Marine Sanctuary. Ship support included HELMSAND, HIEV, KRONSORT, WILHELM PULLWER, PLANET, PELICAN, SEAWARD EXPLORER, GYRE, & SEWARD JOHNSON. Research conducted by this program was

supported by the Office of Naval Research, Dr. Fred Saalfeld, technical director and various basic and applied research programs in the Naval Research Laboratory, Dr. Tim Coffey, technical director. Joint High-Frequency Backscattering Experiments supported by Forschungsanstalt der Bundeswehr für Wassersschall- und Geophysik (FWG), Dr. Peter Wille, director. The Technical Cooperation Program (TTCP) experiments were supported by Australia, Canada, New Zealand, the United Kingdom and the United States.

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2.0 PROJECT REPORTS FOR FY95

The following 19 reports summarize results for projects supported by the CBBLSRP:

2.1 Measurement and Description of Upper Seafloor Sub-Decimeter heterogeneity for Macrostructure Geoacoustic Modeling (Principal Investigators: A.L. Anderson, T.H. Orsi and A.P. Lyons)

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INTRODUCTION

Either predicting acoustic reverberation from the seafloor or application of acoustic data for qualitative seafloor characterization or quantitative inversion requires an understanding of the interaction of an acoustic wave with the seafloor. Such understanding is required for acoustic reflection and scattering from boundaries including both the water-sediment interface and buried interfaces between sediment layers. It is also necessary to include accurately the scattering from volume heterogeneities within the seafloor layers as part of the acoustic seafloor interaction description. It is often true that these interface and volume acoustic interactions are frequency dependent and that different aspects of the interaction will dominate the results for different combinations of parameters (frequency, pulse length, measurement geometry, pulse type and processing, beamwidth, grazing angle, etc.). Various projects of the CBBLSRP are contributing to the needed understanding of some of these acoustic processes, or to describing and understanding the characteristics of the coastal benthic boundary layer of the seafloor which are relevant to the acoustic interaction problem.

This project primarily seeks to characterize the volume heterogeneity of the seafloor on scales from about a decimeter (the nominal diameter of many sefloor samples) down to about 1 mm. A primary tool used here for such characterization is the X-ray computed tomography (CT) scan. The seafloor samples measured for these studies are cylindrical samples recovered by one of three methods: gravity (or piston) cores obtained with samplers operated from a ship, diver cores, or subsamples of box cores. When the purpose of sampling is to investigate free gas within the seafloor, the samples are placed into pressure tight aluminum transfer chambers at the seafloor by divers. Sequential CT scans of these cores, taken as the sample is sequentially moved along its principal axis, results in a three dimensional data base of CT numbers for the entire scanned portion of the core. These CT numbers can be, and in this project are, related to the bulk density of the scanned material. Each CT value represents the bulk density of a very small volume element of the sediment (a typical size of one of these 'voxels' in many of our scans is on the order of 0.3 mm^3). In the absence of bubbles of free gas, the variation of bulk density at high resolution is the primary descriptor sought and quantified for the sediment geoacoustic model. When bubbles of free gas are present in the size range described by the CT technique, then a major goal of this work is to describe the bubble distribution in detail as part of

the seafloor geoacoustic model. We physically subsample many of the cores and measure bulk density of these subsamples both to provide normal, high resolution physical sample density profiles and to serve as part of the calibration for interpretation of CT data as density. We also test the geoacoustic models we thus produce by carrying out some calculations of acoustic interaction with our geoacoustic descriptions.

PROGRESS

During the past year, personnel on this project participated in one more CBBLSRP field experiment: the Key West Campaign. We assisted in selection of coring sites based on acoustic profiler records and other acoustic measurements taken during the early acoustic surveying portion of the campaign. From APL acoustic tower data, a scheme was developed for sampling the seafloor in the acoustic field of view of the tower for our CT scanning work. For this purpose, five diver cores were taken by Mike Richardson and Kevin Briggs upon completion of the APL acoustic measurements. These cores were supplied to us at Key West and they were transported to Texas where they were CT scanned at a petroleum company laboratory in Houston. The cores ranged from 28 to 32 cm in length. All are diver cores taken at the APL site and are identified: KW-PL-214, KW-PL-223-2, KW-PL-228-2, KW-PL-238-1, and KW-PL-238-2. Of these, core number 223-2 was taken from a region in the APL field of view identified as a 'cold spot' (acoustic scattering) while all others come from regions identified as (acoustic backscattering) 'hot spots'. CT scanning and physical sampling of these cores is complete.

The continuing long range collaboration with Fritz Abegg in Kiel has also resulted in additional cores from the gassy sediments of the Baltic. Six additional cores were obtained from Eckernförde Bay in October and November of 1994. These were obtained under pressure in the, now familiar, method by which divers place the cores into pressure tight chambers at the seafloor. Two additional cores were obtained in the same manner from Mecklenburg Bay in September 1995. All of these cores were scanned at the same radiology clinic in Kiel which has been previously used. The most recent of these cores, together with scans of artificial (laboratory constructed) samples, are being used to investigate techniques for increasing the resolution of the CT scan results.

In the annual report for FY94 for this project, a table listed all cores which had been obtained during the first two years of this project and CT scanned for heterogeneity determination. When those previously listed cores are combined with the ones obtained this year, the total number of cores contributing data to the investigations of this project are: Eckernförde Bay: pressure-tight cores - 17 , non-pressure-tight - 8; nearby (Baltic): pressure-tight - 2; Panama City sand sheet: 3; Florida Keys carbonate sediments - 9. These cores range in length from about 30 cm to 5 m. All cores listed have be CT scanned and many have been physically sampled. The data base of CT values resulting from these scans is of the order of 8 Gbytes in size.

As is true with most CBBLSRP investigators, obtaining the cores is only the beginning of the work. In the case of this project, it is also true that carrying out the CT scanning of the core samples is also only an incremental step in the total process of characterizing the geoacoustic

nature of the heterogeneity of the seafloor. For non gassy regions, the characterization is based on the variation of density in the sediment interior.

For gassy sediments, the gas bubbles are a dominant factor in the response of the seafloor to acoustic signals for a wide range of acoustic frequencies. Thus, a primary goal for regions with gas bubbles is the description and characterization of the bubble population. The initial factor quantified for gassy cores is the gas concentration in each core as a function of depth. Such description allows an initial comparison of any given core with other cores from the region. Gas concentration profiles provide valuable insight into the distribution of free gas with depth within the seafloor. They have provided clear indication that the gas bubbles typically are not distributed uniformly with depth but rather occur in thin depth intervals within the seafloor. The acoustic response of gas bubbles is highly frequency dependent and this frequency dependence is related to the bubble size. Thus the prediction of the acoustic response of a bubbly seafloor requires information about the sizes of the gas bubbles and their depth of occurrence. Such information is extracted from the CT data base for the gassy region cores. To illustrate this information, Figures 1 and 2 are provided. These are based on the scanning data for core 315-BS-DC and specifically are for the depth interval of 77 cm to 82 cm below the seafloor. This is a very simple example of a bubbly interval. There is a water (or slurry) filled relict burrow cutting diagonally through this depth interval of the core. Also, within and distributed along the burrow are four moderately large bubbles. External to the burrow, near the depth of one end of the burrow, is another moderately large bubble and several smaller bubbles. This population of bubbles can be clearly identified in three-dimensional images reconstructed from the data base. The gas concentration profile for this interval, in Figure 1, illustrates the influence of this small bubble population on the gas concentration. Figure 2 presents data for the depth of the center of gravity of each gassy feature of this interval and the size of the feature. The size is quantified from the data base as the gas volume of the feature. This volume is represented in the figure as the radius of a spherical feature with the same volume as the actual bubble. The four largest bubbles , which are within the burrow, are easily identified on the size/depth plot as well as the concentration profile. The other bubbles, external to the burrow, can also be identified near the bottom of this depth interval. This collection of a small number of bubbles would only produce a modest scattering of the acoustic energy of an acoustic wave passing through this segment of seafloor. The results shown here are provided to illustrate the results of applying our software for processing segments of the 3-D data base of CT information.

For many depth intervals in most of the cores, there is a significantly larger population of bubbles (sometimes hundreds or even thousands of bubbles). Thus, the interpretation of plots of the bubble population distribution is less straightforward. A similar plot of bubble size (equivalent radius) versus depth (of the bubble center of gravity) is shown in Figure 3 for core P5 (710-BS-DC). This core was collected during the summer 1994 field measurements from the floor of the frequently revisited seafloor pockmark in Eckernförde Bay. Clearly, a vastly larger number of bubbles exist in this 90 cm interval of the pockmark seafloor than in the simple example of Figures 1 and 2. Figure 3 represents one of the most gassy intervals sampled and CT scanned. The gas concentration and distribution in this sample is similar to that noted in other cores we have examined from the pockmark. Most cores from the floor of Eckernförde Bay

outside the pockmark exhibit fewer bubbles than shown in Figure 3 (but many more than in Figures 1 and 2).

The interaction of an acoustic wave with a collection of bubbles within the seafloor produces reflected and scattered returns observable by vertical incidence profiling systems. Modeling this interaction of acoustic energy with the bubbly seafloor can be carried out by a variety of approaches. For an initial examination of the extent to which the seafloor bubbles may contribute to producing the returns observed by acoustic profilers in the CBBLSRP measurements, we have carried out a limited set of simulations. The nature of the returns from the seafloor interval which also exhibits bubbles in the CT scanned cores is characteristic of a scattering process. The return signals appear to be produced by a spatially varying distribution of independent, small, relatively strong localized scatterers. These returns are also of much greater temporal extent than is the transmitted pulse of the profilers. Overall, the bubbly seafloor depth interval produces returns that would be categorized as 'acoustic turbidity.' Thus, we model the bubble/acoustic field interaction as a set of independent single scattering events from the diverse population of bubbles noted in CT scans of cores of the seafloor. Each scatterer is identified by a bubble size and location as measured in the scanned cores. The results of such simulations are encouraging when compared with the spatial and frequency distribution of energy in profiler returns from the region of seafloor sampled by the cores. An example of such comparison is provided in a paper published by some of the personnel of this project (Lyons, Duncan, Anderson and Hawkins 1996, see publications list at the end of this report).

Gas concentration profiles and bubble distributions have been developed for most of the CBBLSRP cores from Eckernförde Bay. Bubbles shapes are being examined. Also under investigation is the variation of bubble populations in the horizontal. This lateral variability has been tested by several 'paired cores' taken at the same general location but separated by distances from 10 cm to 2 m. The degree of such variation is presenting another challenge to developing the appropriate geoacoustic model of bubbly sediment for simulation input. Recent effort has also been devoted to examination of the possibility of extending the CT measurements to a description of smaller bubbles.

Overall, during three years of effort for the CBBLSRP, personnel working on this project have participated in six field expeditions and have obtained samples and data from four others. We have contributed to five international technical meetings and five national meetings in the United States.

OBSERVATIONS

From the three years of field activity, sample description, analysis and modeling, we can make several observations.

It has been demonstrated that bubbles of free gas do exist within the floor of Eckernförde Bay, or at least that they exist is samples recovered from this location and maintained at *in situ* conditions of pressure and temperature.

These gas bubbles are not uniformly distributed in space within the seafloor. They occur rather in relatively thin depth zones (up to a few cm thick) with intervening depth intervals containing few bubbles or none in the size range accessible to x-ray CT scanning description. There is some evidence that the bubble clusters are also patchily distributed in the horizontal.

The size range of bubbles is from an equivalent diameter (equal volume sphere) of 1 mm (the lower limit of CT scanning to date) up to the order of 1 cm. The larger sizes occur in very limited numbers and the number of bubbles of a given size is inversely related to size for the size range examined to date.

In most of the floor of Eckernförde Bay, bubbles within this size range typically do not exist within the upper few decimeters of sediment. Evidence from other CBBLSRP investigators indicates that the depth of the top of the bubbly layer varies seasonally.

Some of the bubbles in this seafloor are almost spherical in shape. However, most of these bubbles are not spherical. They tend to have two long axis ('coin shaped') and it is not uncommon for one of the long axes to be oriented vertically. There is a general tendency away from sphericity as bubble size increases.

Within the floor of the pockmarks of Eckernförde Bay, bubbles occur in larger number, begin to exist at depths of only a few cm at most into the seafloor and have few depth intervals with no gas (are more nearly continuously distributed with depth).

The acoustic interaction with the bubbly sediment zone beginning about 1 m into the floor of Eckernförde Bay is very likely primarily a scattering process for acoustic energy at least over the frequency range from 15 kHz to 40 kHz.

With the possible exception of patchy collections of shells, when they occur, the gas bubbles are the predominate source of returned acoustic energy from beneath the water-sediment interface of Eckernförde Bay for this frequency range. A possible exception to this would be regions without bubbles in the size range described but with some bubbles of a much smaller size.

Internal volume scattering from heterogeneities within the upper few cm of the sand sheet seafloor off Panama City, Florida is probably not a significant contributor to profiler normal incidence returns at frequencies near 40 kHz. This is also true for other acoustic energy interacting with this seafloor at other grazing angles down to about 10 degrees. For even lower grazing angles, volume scattering from the lognormally distributed (size) particles may predominate in the overall seafloor backscattered return.

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* THO is now employed at Planning Systems Inc., Slidell, Louisiana
** APL is now employed at the SACLANT Research Centre, La Spezia, Italy

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A.P. Lyons, M.E. Duncan, A.L. Anderson and J.A. Hawkins 'Predictions of the acoustic scattering response of free-methane bubbles in muddy sediments' accepted for publication in J. Acoust. Soc. Am., January 1996, 10 pp.

T.H. Orsi and A.L. Anderson 'X-ray computed tomography of macroscale variability in sediment physical properties, offshore Louisiana' Gulf Coast Association of Geological Societies Transactions, Vol. 45, pp. 475-480, 1995 also presented at the GCAGS Convention, Baton Rouge, Louisiana, October 1995; abstract published in AAPG Bulletin, vol. 79, no. 10, p. 1565, 1995.

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A.P. Lyons, M.E. Duncan, J.A. Hawkins and A.L. Anderson 'Predictions of the acoustic response of free methane bubbles in muddy sediments' invited paper presented at the special session on High Frequency Inversions for Sediment Properties at the 128th meeting of the Acoustical Society of America in Austin, Texas, November 28, 1994, abstract published in J. Acoust. Soc. Am., V. 96, N. 2, pt 2, 3217, 1994.

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T.H. Orsi, A.L. Anderson and A.P. Lyons 'Geoacoustic characterization of shallow-water marine sediments for high-frequency applications' IEEE-OES OCEANS 94, Brest, France, September 13-16, 1994, Proceedings Vol I:866-871.

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A.P. Lyons and T.H. Orsi 'Characterization of seafloor property variability and estimates of acoustic volume scattering cross section in Eckernförde Bay, Germany' 6th Annual Student Symposium, College of Geosciences and Maritime Studies/Ocean Drilling Program, Texas A&M University, College Station, TX, February 19, 1994.

T.H. Orsi 'A method for quantifying bubble characteristics in gassy aqeous sediments' 6th Annual Student Symposium, College of Geosciences and Maritime Studies/Ocean Drilling Program, Texas A&M University, College Station, TX, February 19, 1994.

T.H. Orsi and A.L. Anderson 'Computer tomography of biological structures in marine sediments' IEEE-OES OCEANS 93, Victoria, Canada, September, 1993.

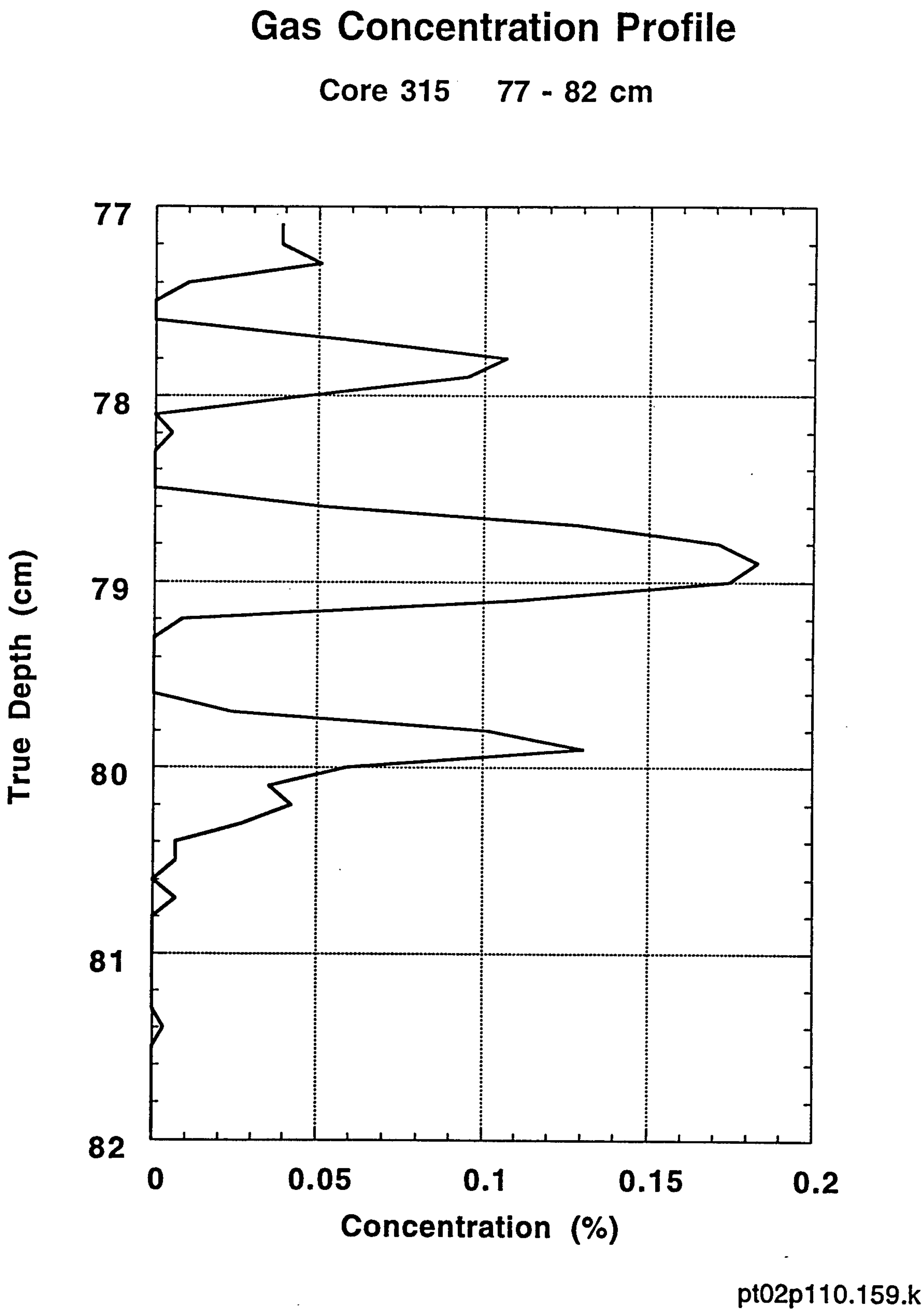

Figure 1. Gas concentration profile for a segment of core 315-BS-DC.

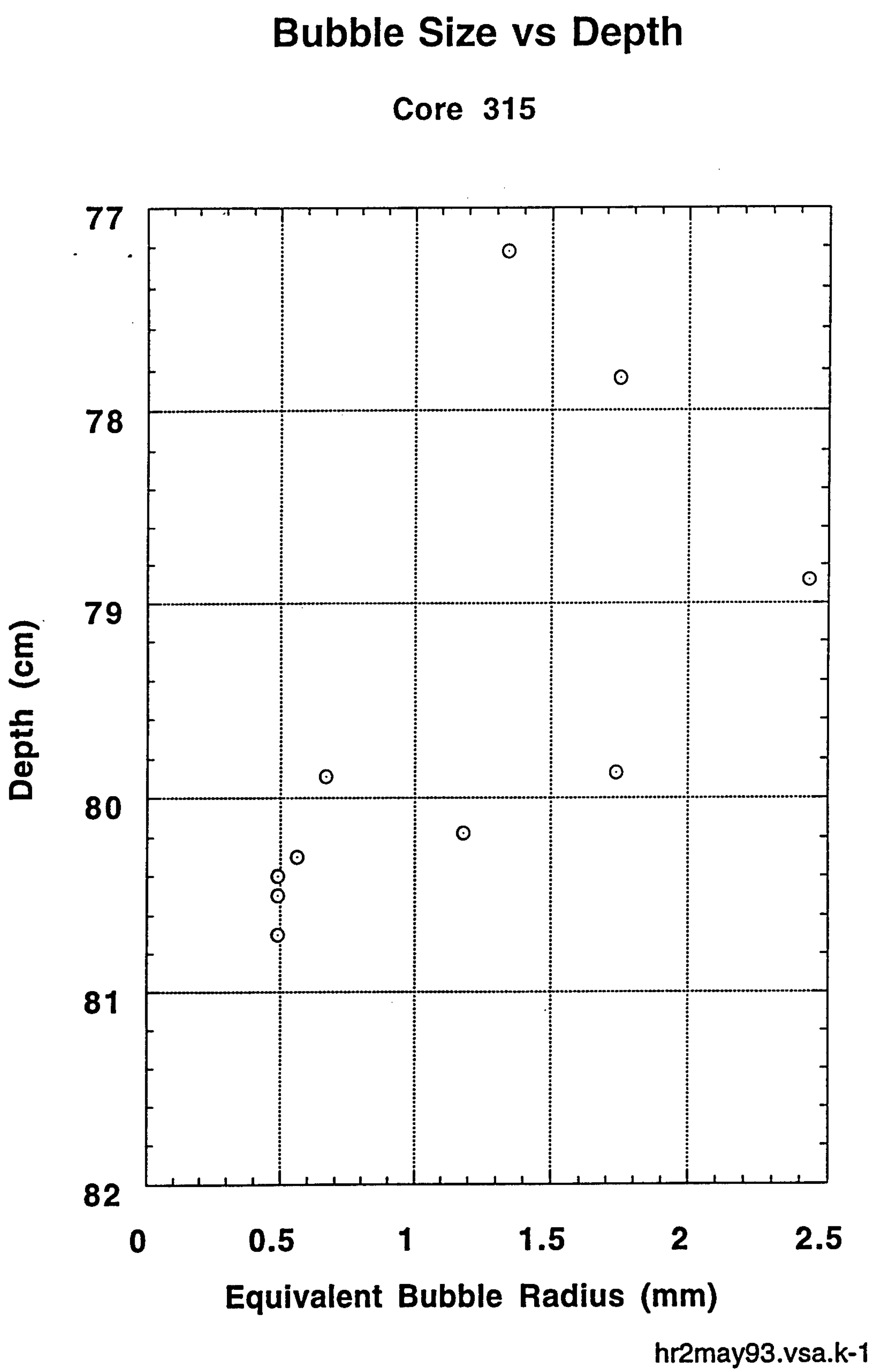

Figure 2. Bubble size vs depth for a segment of core 315-BS-DC.

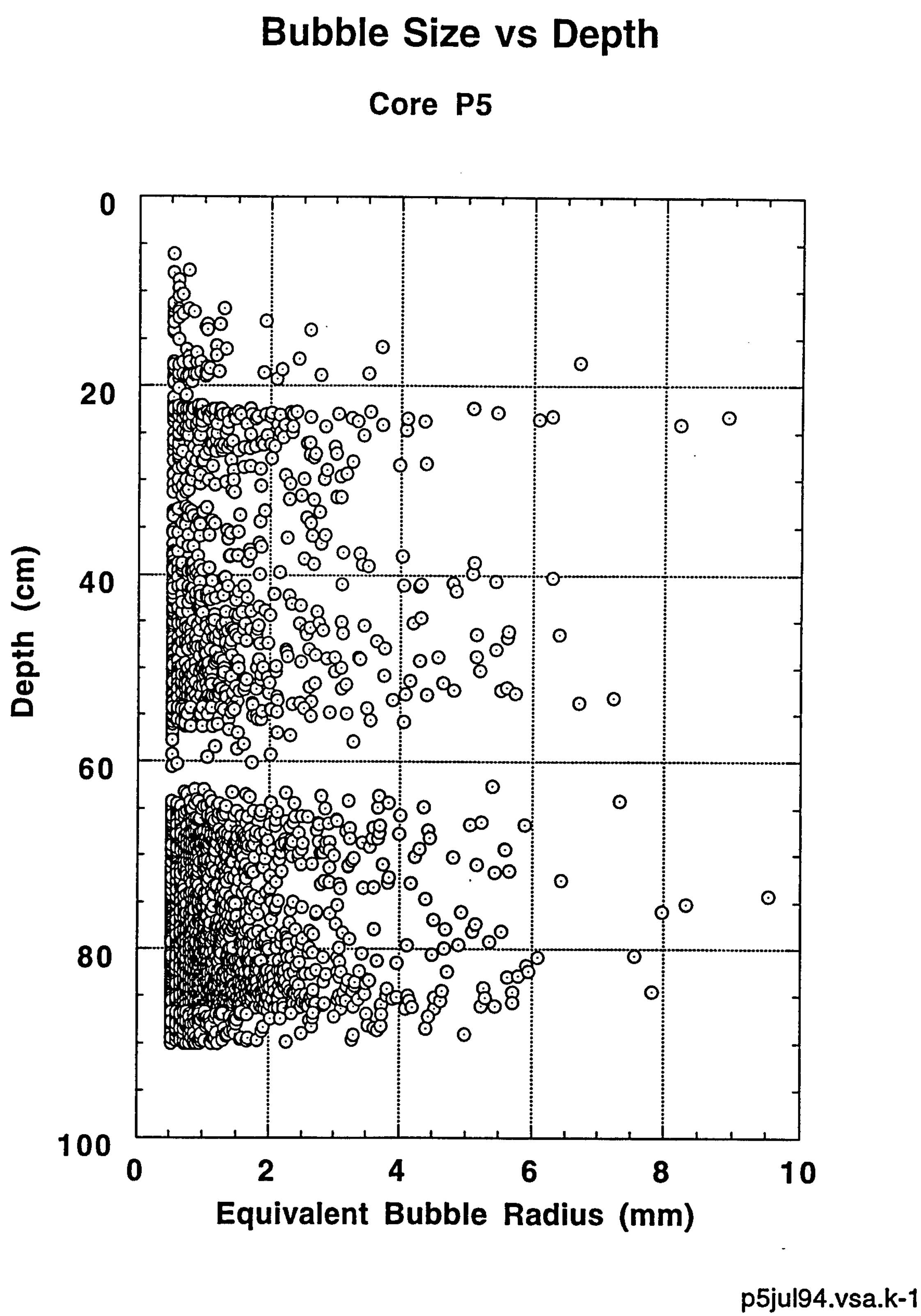

Figure 3. Bubble size vs depth for pockmark core 710-BS-DC (P5)

2.2 Sediment Properties from Grain and Microfabric Measurement (Principal Investigators: R.H. Bennett, D.M. Lavoie and M.H. Hulbert)

Richard H. Bennett, Dennis M. Lavoie (NRL),
and Matthew H. Hulbert (Resource Dynamics, Inc.)

INTRODUCTION

The **overall hypothesis** guiding this project is that sediment microfabric provides the fundamental control on sediment macro-scale mechanical properties and behavior. The term microfabric encompasses both the micro-scale structure of sediment (i.e., the physical arrangement of constituents) and the physico-chemical forces among the constituents that influence the structure. Our premise is that, if we can describe the nature of the solid constituents and their spatial relationships (microfabric), we can provide insight into the physical properties. Furthermore, if microfabric can be quantified properly, we may begin to estimate the physico-chemical forces involved in the association. This knowledge is necessary for development of constitutive models of sediment structure and, subsequently, for the development of continuum models that deal with sediment macro-scale dynamic response to environmental processes and stresses.

The **scientific objective** of the project, then, is to examine qualitative and quantitative descriptions of microfabric of selected sediments and relate them to the bulk physical properties of those sediments.

The **general approach** is to use current methods for the qualitative study microfabric and extend them to produce quantitative data in both 2D and 3D. Quantification will rely on computerized image analysis and volume reconstruction techniques. The work will be done in close coordination with other CBBL investigators so that coincident samples are collected for both microfabric and physical properties measurements.

PROGRESS AND CURRENT STATUS

Despite funding constraints, significant work was completed on both the Eckernförde and Key West sites. **Accomplishments for FY95** include:

- Completion of Key West Campaign. Subsamples collected for microfabric analysis include material from gravity cores and x-radiograph cores and were collected concurrently with Dawn Lavoie's and Yoko Furakawa's samples for physical properties and geochemistry.

- Preliminary image porosity analyses of Key West samples.

- Submission of two manuscripts to GeoMarine Letters CBBL special volume: one on the relationship of microfabric to physical properties at the Eckernförde study site; one on the in situ pore pressure field at the Eckernförde study site. In addition, a short technical note has been accepted by Journal of Sedimentary Research on the use of the mini-corer technique for microfabric subsampling.

- Joint poster presentation at SEPM in St. Petersburg.

- Although not an explicit task of our project, we also fielded a piezometer during the Key West experiment, the first time this instrument has been deployed in carbonate sediment.

Current status of the project: Our current efforts are focused on preparing the remainder of the Key West samples, obtaining digitized SEM and TEM images, and comparing quantitative image porosity to physical and index properties measured on coincidentally-collected samples. In addition we are beginning the collection of serial ultra-thin section digital images for high resolution volume reconstruction.

RESULTS

Eckernförde Site

Our efforts at quantitative image analysis on the Eckernförde samples have concentrated on examining 2-dimensional porosity through TEM and ultra-thin sections (~200-300 nm) and relating it to bulk physical properties. Unlike the Mississippi Delta sediment described quantitatively by Bennett, Bryant, and Kellar (J. Sed. Pet. 23:217, 1981), image analysis of Eckernförde sediment proved surprisingly difficult due to: (a) high spatial variability in the sediment at small scales; (b) prevalence of low contrast smectite particles which hampered assignment of pixels to "solid" or "void" categories; (c) void areas that were large compared to the imaging capacity of the TEM (i.e., a scale mismatch between the phenomenon and observation tool). The first two problems were attacked by analyzing multiple fields and bracketing the threshold value that divided solids from void. The third problem, large voids that occupy most or all of the TEM frames, was more troublesome. Inclusion of such frames in analyses of porosity badly skewed the statistics of the measurement. As a result, our analyses were based on non-randomly selected fields, and porosity as measured by image analysis was 5-15% lower than reported for bulk porosity. These large features are the channels that were reported in last year's report. Standard petrographic thin sections examined by light microscopy confirmed that the sediment is indeed highly pelletized with relatively large channels between the pellets. Image porosity measurements within clay particle aggregates (which are presumably remnants of pellets) indicated significantly lower values (95% confidence level) within these structures (mean of 59% ± 4.6) than for overall image porosity (mean of 71% ± 3.7) and for bulk porosity (~82%). The heterogeneous distribution of porosity, and that of the biogenic particles, suggest that diagenesis, geochemistry (including sulfide and methane production), and physical properties of this sediment will all diverge from

predicted results. It is postulated that the unexpected results of grain size, consolidation, and permeability analyses are in fact due to the unusual microfabric of this sediment.

Key West Sites

Preliminary results of microfabric analyses indicate that a large portion of the porosity in these sediments is intraparticle porosity, i.e., pores among the aragonitic crystals making up Halimeda plates and within enclosed shells such as foraminifera. Bulk porosities of these sediments were on the order of 55%. Image analysis of interparticle porosity found only about 30%. Image analysis of Halimeda plate fragments found an additional approximately 25%. (An incidental finding was that these samples are extremely destructive of the diamond knives used to cut the ultra-thin sections!) Again, the way porosity is distributed within this sediment may be significant in understanding and modeling its properties and behavior.

PRELIMINARY CONCLUSIONS OF SIGNIFICANCE TO CBBL OBJECTIVES

A) Image porosity cannot be compared directly to bulk porosity except, perhaps in the case of homogeneous sediments. The chief, and not insignificant, use of image porosity analyses is to determine how porosity, and thus permeability, is distributed within the sediment structure.

B) Heterogeneous distribution of porosity and permeability within the sediment can be expected to have effects on physical properties and geochemistry that would not be predicted based on analyses of bulk index properties.

C) Microfabric description, coupled with quantitative analysis, can provide a scientific basis for understanding anomalous physical properties and behavior of sediments.

D) Microfabric characterization may be required to identify the largest possible "functional unit" in the sediment structure for inclusion in micromechanical models of microfabric.

CUMULATIVE LIST OF PUBLICATIONS

Workshops

Bennett RH, Meyers MM, Lavoie DM, Hulbert MH, Stewart S, and Litman E, 1994. "Sediment Pore Pressure and Permeability in Eckernförde Bay, Germany." Gassy Muds Workshop, Kiel, Germany. July 1994.

Lavoie DL, Lavoie DM, Pittenger HA, and Bennett RH, 1994. "Microfabric Predictors of Sediment Properties". Gassy Muds Workshop, Kiel, Germany. July 1994.

Lavoie DL, Lavoie DM, Furukawa Y, and Briggs K, 1995. "Comparison of Sediment Properties along the Schock Line and the NRL Site, Eckernförde, Germany." Modeling of Methane-rich Sediments of Eckernförde Bay Workshop, Eckernförde, Germany. June 1995.

Reports

Bennett RH, Lavoie DL, Lavoie DM, Sawyer WB, Hunter NW, Meyer MM, Kennedy CS, and McCrocklin K, 1995. "Mass Physical and Mechanical Properties of Sediments from the Chesapeake Bay near the Mouth of the Patuxent River." NRL Report No. NRL/PU/7430-95-0008, Naval Research Laboratory, Stennis Space Center, MS 39529

Presentations

Bennett RH, Lavoie DM, Meyers MM, Litman E, and Stewart S, 1994. "Pore Pressure Field in Eckernfoerde Bay, Germany." Proceedings of the Ocean Sciences Meeting, American Geophysical Union-American Society of Limnology and Oceanography. San Diego, CA. 1994

Lavoie DM, Bennett RH, Chiou W-A, Baerwald RJ, and Hulbert MH, 1994. "Sediment Microfabric of Gassy Sediments in Eckernförde Bay." Proceedings of the Ocean Sciences Meeting, American Geophysical Union-American Society of Limnology and Oceanography. San Diego, CA. 1994

Lavoie DL, Lavoie DM, Richardson MR, and Furukawa Y, 1995. "Relationships among Geotechnical and Geoacoustic Properties and Microfabric in Florida Carbonate Sediments." Proceedings of the 1st SEPM Congress on Sedimentary Geology, St. Petersburg, FL. SEPM

Papers

Bennett RH, Hulbert MH, Meyer MM, Lavoie DM, Briggs K, Lavoie DL, Baerwald RJ, and Chiou W-A, 1996. "Fundamental Response of Pore Water Pressure to Microfabric and Permeability Characteristics: Eckernförde Bay." Geo-Marine Letters (in press).

Lavoie DM, Lavoie DL, Pittenger HA, and Bennett RH, 1996. "Bulk Sediment Properties Interpreted in Light of Qualitative and Quantitative Microfabric Analysis." Geo-Marine Letters (in press).

Lavoie DM, Bennett RH, Baerwald RJ, and Hulbert MH, 1996. "A Drinking Straw Mini-corer for Sediments." Journal of Sedimentary Research, Section A (in press).

2.3 High-Frequency Acoustic Scattering from Sediment Surface Roughness and Sediment Volume Inhomogeneities (Principal Investigators: K.B. Briggs and M.D. Richardson)

Kevin Briggs and Michael Richardson, NRL Code 7431, Stennis Space Center, MS 39529-5004

Objectives

Investigators characterized sediment volume heterogeneity in order to better understand geoacoustic variability at the Dry Tortugas, Marquesas Keys and Rebecca Shoal experiment sites. Investigators also characterized the sediment interface roughness within the ensonified area of the Dry Tortugas experiment site both before and after diver manipulation. Laboratory analyses of sediment porosity, compressional wave velocity and attenuation, grain size distribution and grain density from the FY93, FY94 and FY95 experiments were completed. In addition, sediment density to x-rays, electrical resistivity and sediment shear strength were measured at the Dry Tortugas experiment site. Smith-McIntyre grabs were collected to provide ground truth on variability of sediment grain size at the locations where ISSAMS data were collected.

Of particular importance to this effort was the spatial variability of sediment porosity and density in three dimensions in the Dry Tortugas experiment area. These measures were obtained through the use of a network of resistivity-sensing electrodes inserted into a freshly collected box core. X-radiography and Peter Jackson's electrical resistivity core measurements on x-radiograph cores were used to obtain two-dimensional spatial variability of sediment porosity and density.

Accomplishments

<u>FY93-94 Data (Eckernförde)</u>

Grain size distribution and porosity were measured on sediments collected from gravity cores collected from the NRL experiment site and along the "Schock line" from Stollergrund to Mittelgrund in order to ground truth sedimentation patterns controlling acoustic properties. Grain size distribution and porosity of sediment collected from five box cores along the "Schock line" were measured. Three of the five box cores collected along the line yielded x-radiograph subcores for sediment microstructure analysis.

Sediment mean grain size and porosity for cores 614 and 640 at the experiment site were similar to previous cores (302, 303) in that values did not deviate remarkably from mean values of 10.6 phi and 85%, respectively, from 50 to 450 cm sediment depth (Figs. 1 and 2). Mean grain size was measured from nine diver cores collected at the NRL experiment site. In the top 35 cm, sediment mean grain size varied little from a mean value of 9.8 phi (Fig. 3).

Along the Schock line, sediments exhibited the greatest variability in porosity in the top meter of sediment, and appeared to converge deeper in the sediment (Fig. 4). Depth profiles of mean grain size along the Schock line are presented in Fig. 5. Finer scale measurements (every 2 cm) of

sediment porosity and mean grain size in Figs. 6 and 7 indicate the fine laminations present from transport of coarser sediments from bathymetric rises to the troughs between them.

Key West

Twenty-two 6.1-cm-diameter cores were collected from the WFS PLANET in February 1995 for the purpose of measuring sediment compressional wave velocity and attenuation, grain size and porosity. Two cores were collected from box cores in the area north of the Marquesas Keys, two diver cores were collected from Rebecca Shoal and eighteen diver cores were collected south of Garden Key in the Dry Tortugas. Seven x-radiographic cores were collected in the Marquesas Keys area. In addition, sediment shear strength was measured with a hand-held torque vane by divers to a sediment depth of 65 cm. Sediment porosity was determined from fifteen cores, sediment grain size distributions were determined from twelve cores collected in 1995 and five cores collected for the site survey in 1994. A video camera drift was performed across the center of the Dry Tortugas experiment site. Five fifteen-meter transects (four from the Dry Tortugas site and one from the Marquesas Keys site) were photographed with a stereo camera in order to measure interface roughness. Only two and a half transects, all from the Dry Tortugas site, are available for analysis due to a mishap in the film developing process.

Sediments in the Marquesas Keys and Dry Tortugas were carbonate sand-silt-clays with varying amounts of mollusk shell hash (mean weight % gravel: 5.8 and 0.7%, respectively). Rebecca Shoal sediments were coarse to medium carbonate sands transported by strong tidal currents as several-meter-high sand waves. Values of sediment shear strength at the Dry Tortugas site were very high for sediment depths greater than 10 cm, as a result of the presence of embedded shells and other coarse particles within the silt-clay matrix (Fig. 8). Figure 9 shows the measured velocity, attenuation, porosity and mean grain size with depth in the sediment at the Dry Tortugas site. Sediment compressional wave velocity averaged 1551.6 m s^{-1} with a coefficient of variation of 0.62%. Sediment compressional wave attenuation averaged 332 dB m^{-1} with a coefficient of variation of 14.3 %. Sediment porosity averaged 58.4 % with a coefficient of variation of 7.65%. Sediment mean grain size averaged 6.6 phi with a coefficient of variation of 5.81%.

Areas indicated as "hot spots" and "cold spots" by the 40 kHz sonar operated by APL-UW were sampled with diver cores. Cold spots were characterized by finer, higher porosity layers at and immediately below the sediment-water interface. Hot spots may have been localized pockets of near-surface infauna engaging in burrowing and feeding activities. Surprisingly, values of porosity in the upper few centimeters were not greater in hot spots. A possible explanation is that faunal activity in hot spots may act to destabilize surface sediments, thus making them more susceptible to erosion by currents. Transport of destabilized sediment from the hot spots exposes a sediment-water interface more similar in character to the lower-porosity sediment buried 2-3 cm below the non-eroded interface.

Preliminary Conclusions

Eckernförde

oVertical variability of sediment compressional wave velocity and attenuation, porosity and mean grain size in the sediments of Eckernförde is low from the sediment surface to near 35 cm into the sediment. Variability of compressional wave velocity and attenuation increases significantly below 35 cm with no concomitant change in variability of sediment porosity or mean grain size; an indication of the presence of free gas.

oVane shear strength values generally increased with depth and showed some variability below 50 cm depth in the sediment, corresponding to the depth where free gas presumably exists.

oElectrical resistivity measurements of x-ray cores show lateral and vertical variability that correspond well with x-ray density measurements. These results promise the ability to ascertain the autocorrelation function describing both vertical *and* horizontal fluctuations in density.

Key West

oThe carbonate sediments from the Dry Tortugas and Marquesas Keys experiment areas exhibit variability in sediment sound velocity and attenuation and mean grain size largely due to the presence of mollusk shell fragments deeper than 5-10 cm in the sediment. The values for these parameters in the Dry Tortugas site are less variable than in the Marquesas Keys site.

oPorosity exhibits a strong gradient with increasing depth in the sediment, but only in the top 10 cm.

oSediment shear strength values exhibit a steep depth gradient and high variability below 10 cm sediment depth, primarily due to the presence of mollusk shell fragments embedded in the sand-silt-clay matrix.

oDifferences in sediment physical and geoacoustic properties between acoustic "hot spots" and "cold spots" (as defined by APL-UW) are probably due to changes in bulk properties effected by burrowing crustaceans. High-porosity, fine-grained sediment in cold spots represent localized areas of sediment accumulation and lower-porosity, coarser-grained sediment represent localized areas of bioturbation which destabilize sediment and facilitate transport of the high-porosity, fine-grained surface sediment.

Significance of Results to CBBL Objectives

We have successfully characterized the sediment-water interface roughness and the velocity and density contrasts for the purpose of modeling backscatter intensity using the composite roughness model. We are attempting to characterize the buried inhomogeneities for modeling purposes by subjecting the 3-dimensional resistivity data to mathematical analysis in order to yield a correlation function in three dimensions (two horizontal and one vertical axes). By obtaining these numerical

descriptors of the features controlling acoustic scattering from the sea floor, we are then able to improve existing models predicting bottom backscattering.

Presentations and Publications

Briggs, K.B., M.D. Richardson and D.B. Percival. 1994. Correlation functions estimated from vertical profiles of sediment porosity and compressional wave velocity fluctuations. *EOS*, 75: 202.

Briggs, K.B. and M.D. Richardson. 1994. Geoacoustic and physical properties of near surface sediments in Eckernförde Bay. *Gassy Mud Workshop*, FWG, Kiel, Germany. In press.

Briggs, K.B. 1994. Correlation functions for sediment acoustic properties. *J. Acoust. Soc. Am.*, 96: 3245-3246.

Briggs, K.B., M.D. Richardson and D.R. Jackson. 1994. High-frequency bottom backscattering: volume scattering from gassy mud. *J. Acoust. Soc. Am.*, 96: 3218.

Briggs, K.B. and M.D. Richardson. 1995. Physical property variability in sediments in and proximal to Eckernförde Bay. In, Wever, T.F. (ed.), *Proceedings of the Workshop Modelling Methane-Rich Sediments of Eckernförde Bay.* Eckernförde, Germany, 26-30 June 1995, pp. 208-214.

Briggs, K.B. and M.D. Richardson. 1995. Geoacoustic and physical properties of carbonate sediments from the Key West Campaign. SEPM Congress on Sedimentary Geology, St. Petersburg, FL, 13-16 Aug. 1995, p. 33.

Briggs, K.B. and M.D, Richardson. (in review). Variability of in-situ shear strength of gassy sediments. *Geo-Mar. Ltrs.*

Briggs, K.B. and M.D. Richardson. (submitted). Small-scale fluctuations in acoustic and physical properties in surficial carbonate sediments. *EOS.*

Bennett, R.H., M.H. Hulbert, M. Meyer, D.M. Lavoie, **K.B. Briggs**, D.L. Lavoie, R.J. Baerwald, and W.-A. Chiou. (in review). Fundamental response of pore water pressure to microfabric and permeability characteristics: Eckernförde Bay. *Geo-Mar. Ltrs.*

Holyer, R.J., D.K. Young, J.R. Chase and **K.B. Briggs**. 1994. Sediment density structure inferred by textural analysis of cross-sectional x-radiographs and electron microscopy images. *EOS*, 75: 202.

Holyer, R.J., D.K. Young, J.C. Sandidge, and **K.B. Briggs**. (in review). Sediment density structure derived from textural analysis pf cross-sectional x-radiographs. *Geo-Mar. Ltrs.*

Jackson, D.R., K.L. Williams, and **K.B. Briggs**. (in review). High-frequency acoustic observations of benthic spatial and temporal variability. *Geo-Mar. Ltrs.*

Jackson, P.D., **K.B. Briggs**, R.F. Flint, M.A. Lovell and P.K. Harvey. 1994. Evaluation of the porosity structure of coastal benthic boundary layer sediments using micro-resistivity imaging. *EOS*, 75: 201.

Jackson, P.D., **K.B. Briggs**, R.F. Flint, M.A. Lovell and P.K. Harvey. 1994. The investigation of millimeter scale heterogeneity in Coastal Benthic Boundary Layer sediments using microresistivity and x-ray imaging of "diver" cores. *J. Acoust. Soc. Am.*, 96: 3245.

Jackson, P.D. and **K.B. Briggs**. 1995. Evaluation of heterogeneity within gas-rich sediments using micro-resistivity imaging and x-radiography. In, Wever, T.F. (ed.), *Proceedings of the Workshop Modelling Methane-Rich Sediments at Eckernförde Bay.* Eckernförde, Germany, 26-30 June 1995, pp. 215-216.

Jackson, P.D. and **K.B. Briggs**. (in review). Evaluation of sediment heterogeneity using micro-resistivity imaging and x-radiography. *Geo-Mar. Ltrs.*

Lavoie, D., **K.B. Briggs**, M. Richardson, R. Stoll and A. Pittenger. (in review). Panama City sands: geotechnical and geoacoustic variability. *Geo-Mar. Ltrs.*

Richardson, M.D., S. Griffin and **K.B. Briggs**. 1994. In-situ sediment geoacoustic properties: a comparison of soft mud and hard packed sand sediments. *EOS*, 75: 220.

Richardson, M.D. and **K.B. Briggs**. (in review). In-situ and laboratory geoacoustic measurements in soft mud and hard-packed sand sediments. *Geo-Mar. Ltrs.*

Stephens, K., D.L. Lavoie, Y. Furakawa and **K.B. Briggs**. 1995. Variability of physical properties from the Dry Tortugas and Marquesas Keys. SEPM Congress on Sedimentary Geology, St. Petersburg, FL, 13-16 Aug 1995, p. 117.

Correlation functions estimated from vertical profiles of sediment porosity and compressional wave velocity fluctuations. AGU-ASLO Ocean Sci. Meeting, 21-25 February 1994, Town and Country Hotel, San Diego, CA.

Geoacoustic and physical properties of near surface sediments in Eckernförde Bay. Gassy Mud Workshop, 11-12 July 1994, FWG, Kiel, Germany.

Correlation functions for sediment acoustic properties. ASA Meetings, 28 Nov-2 Dec 1994, Stouffer Austin Hotel, Austin, TX.

High-frequency bottom backscattering: volume scattering from gassy mud. ASA Meetings, 28 Nov-2 Dec 1994, Stouffer Austin Hotel, Austin, TX.

Physical property variability in sediments in and proximal to Eckernförde Bay. Workshop Modelling Methane-Rich Sediments of Eckernförde Bay, 26-30 June 1995, Stadthotel, Eckernförde, Germany.

Geoacoustic and physical properties of carbonate sediments from the Key West Campaign. SEPM Congress on Sedimentary Geology, 13-16 August 1995, TradeWinds Resort Convention Center, St. Petersburg, FL.

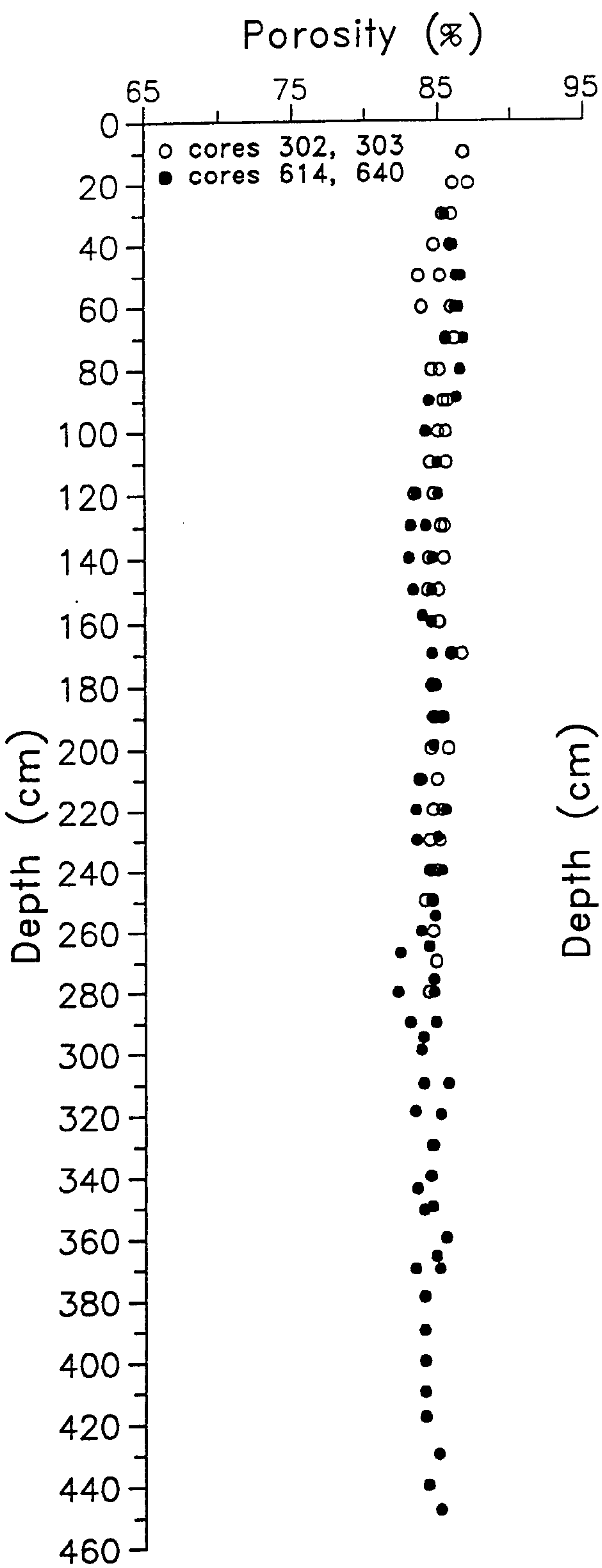

Fig. 1. Sediment porosity measured from four gravity cores collected at the NRL experiment site.

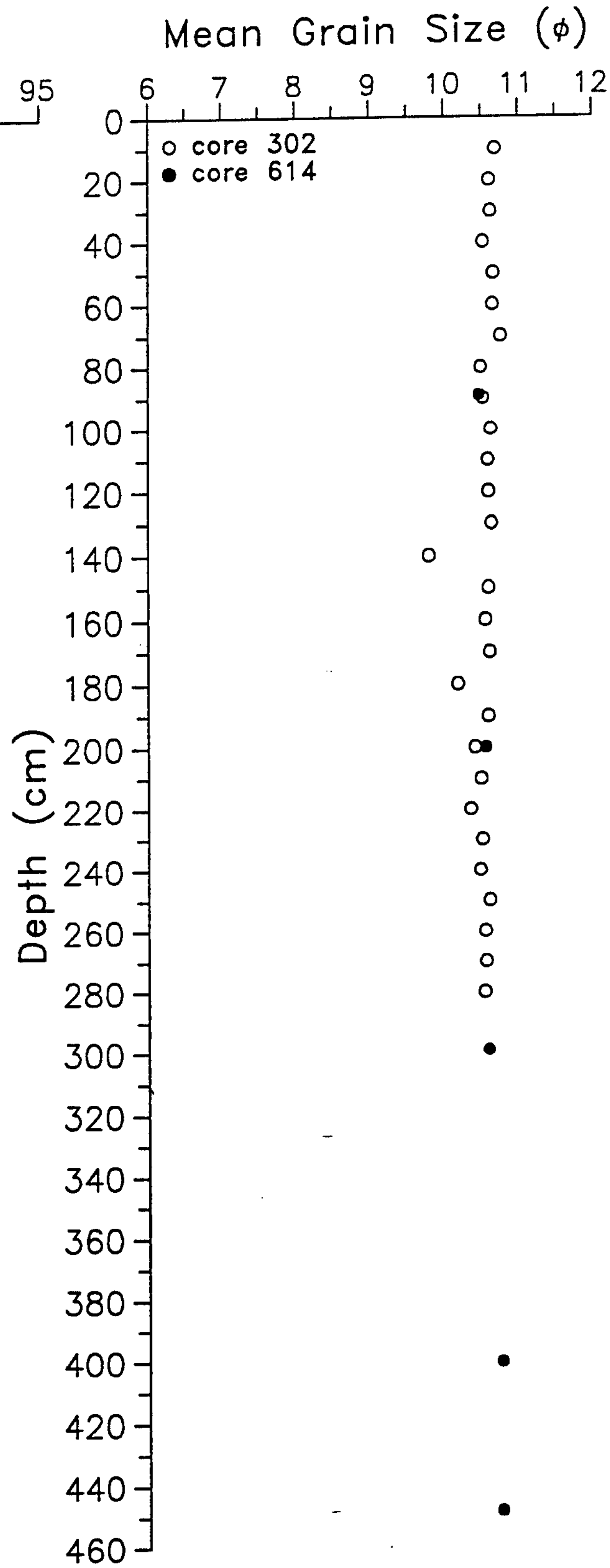

Fig. 2. Sediment mean grain size in phi units for gravity cores collected at the NRL site.

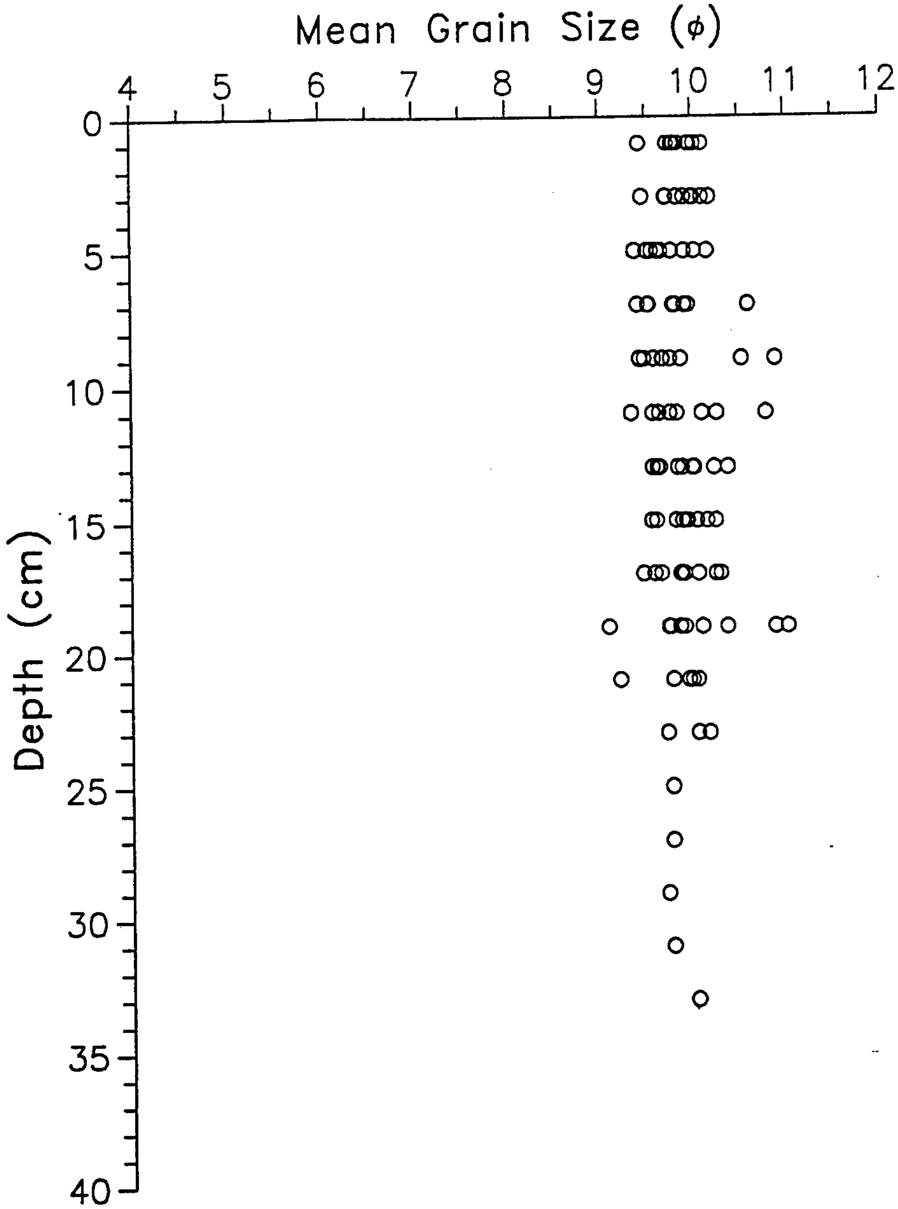

Fig. 3. Mean grain size (phi) measured from nine diver cores collected at the NRL experiment site.

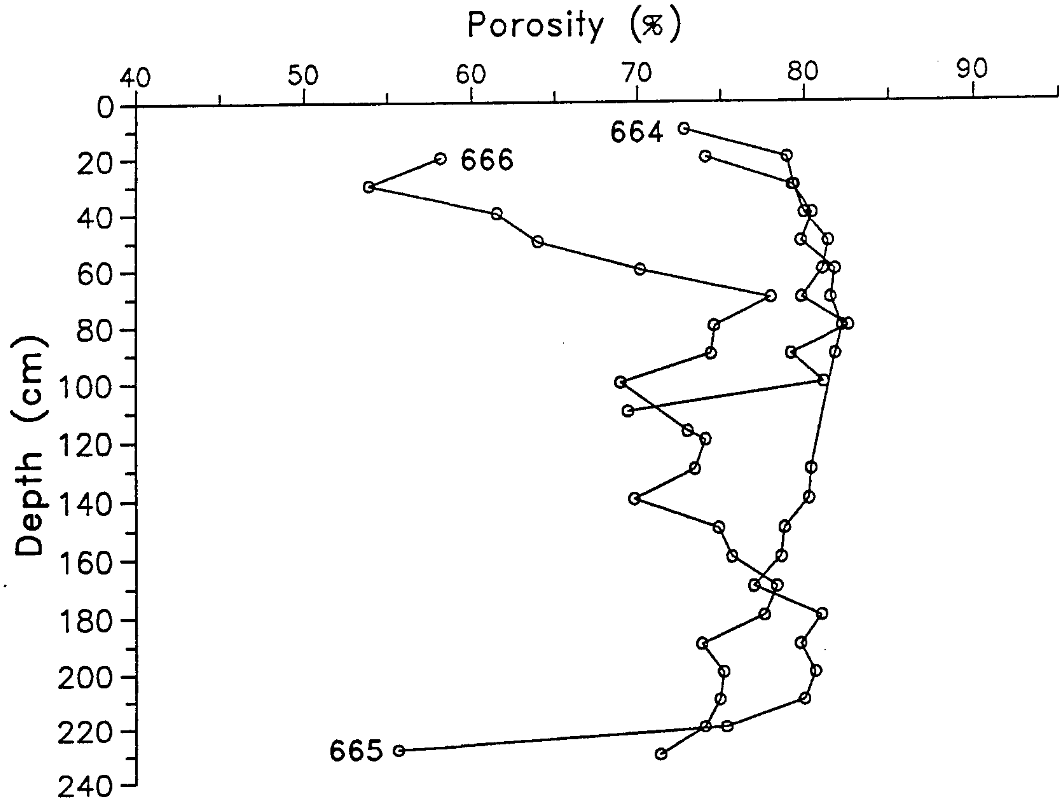

Fig. 4. Sediment porosity from gravity cores along the transect from Mittelgrund to Stollergrund (664–666).

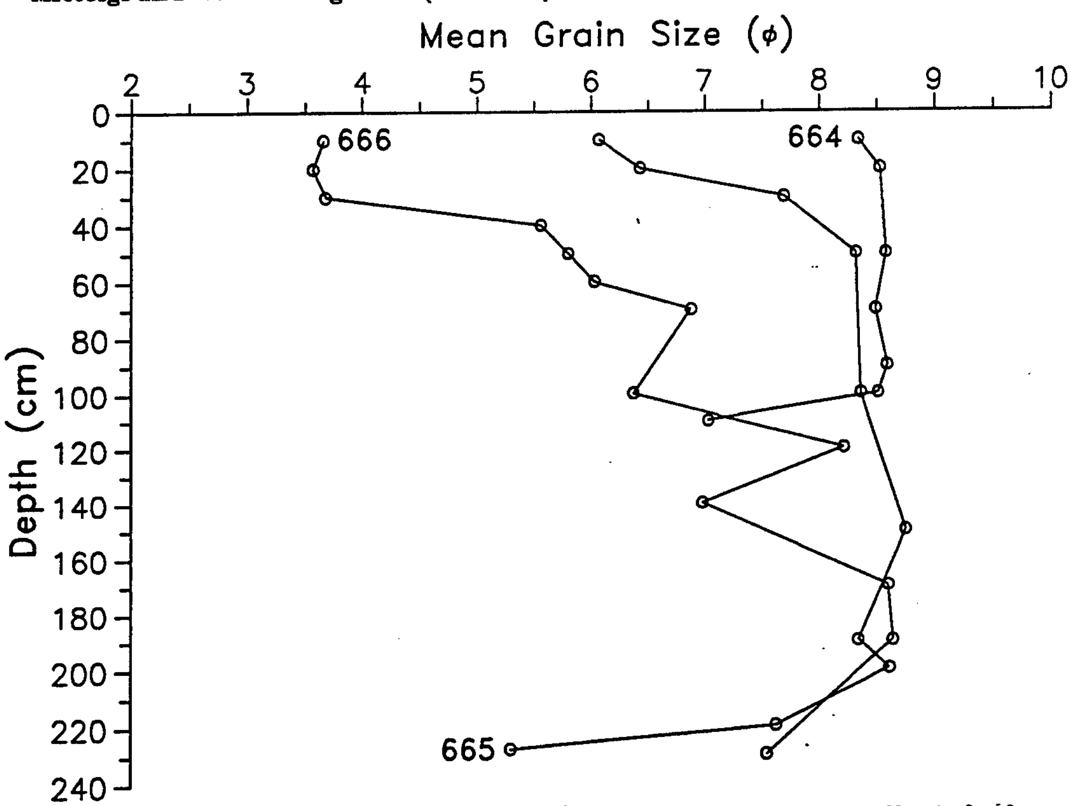

Fig. 5. Sediment mean grain size (phi) from gravity cores collected along the transect from Mittelgrund to Stollergrund (664–666).

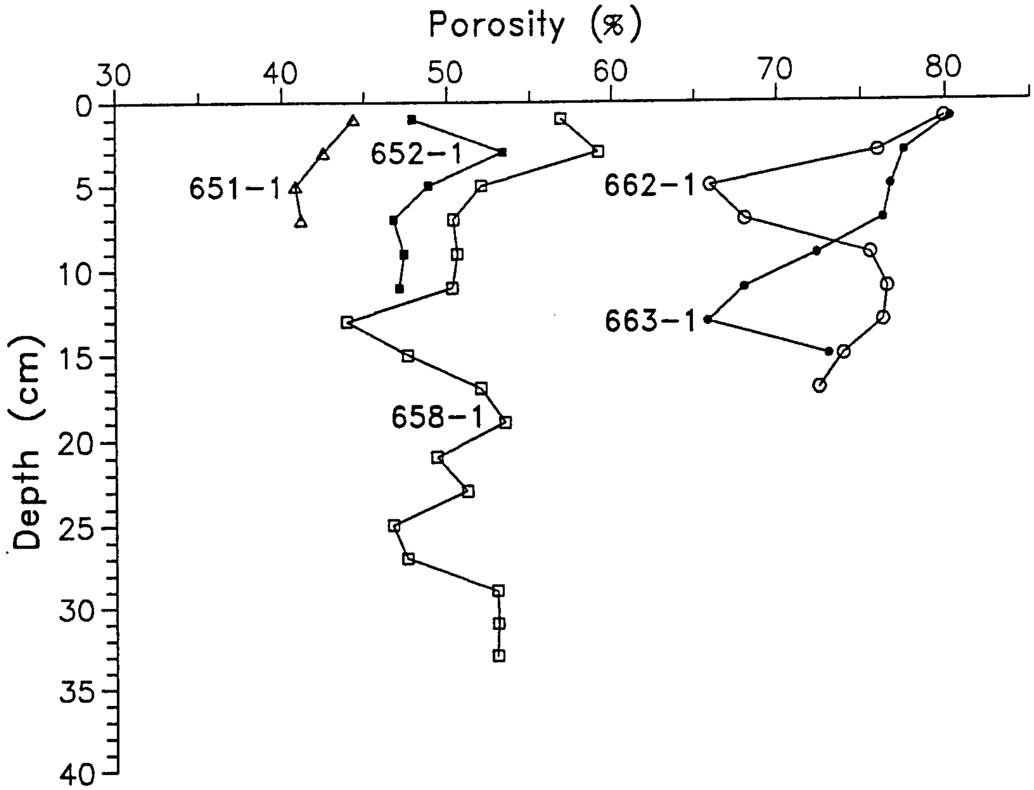

Fig. 6. Sediment porosity measured from box cores collected along the transect from Stollergrund to Mittelgrund (left to right).

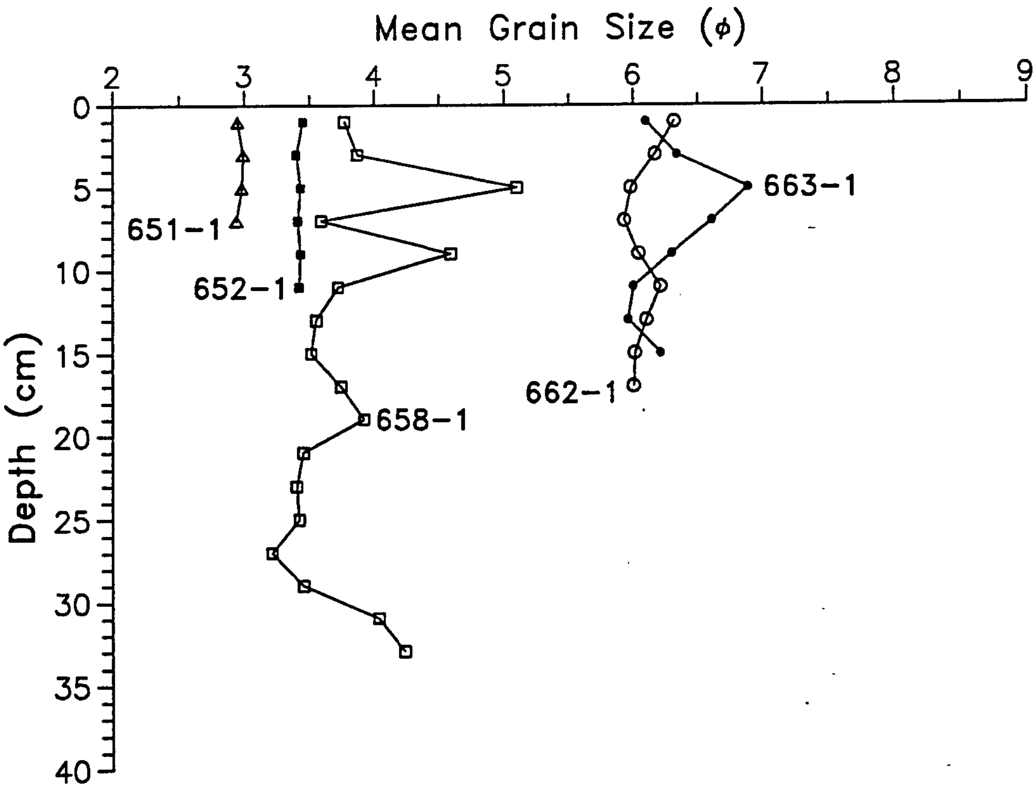

Fig. 7. Sediment mean grain size measured from box core samples collected along the transect from Stollergrund to Mittelgrund.

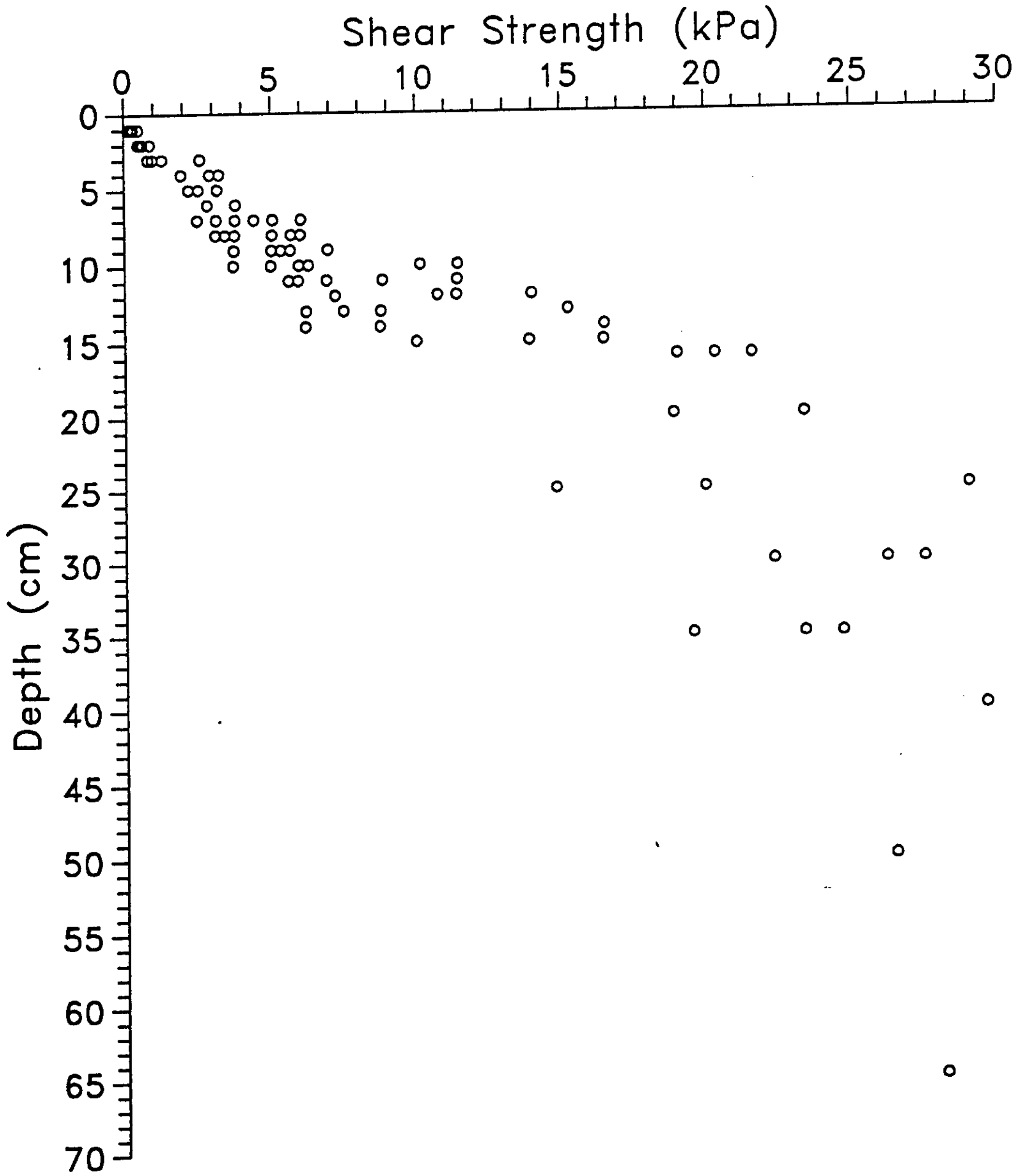

Figure 8. Sediment shear strength measured with the diver hand-held torque gauge. Shaft friction is subtracted from the measurements.

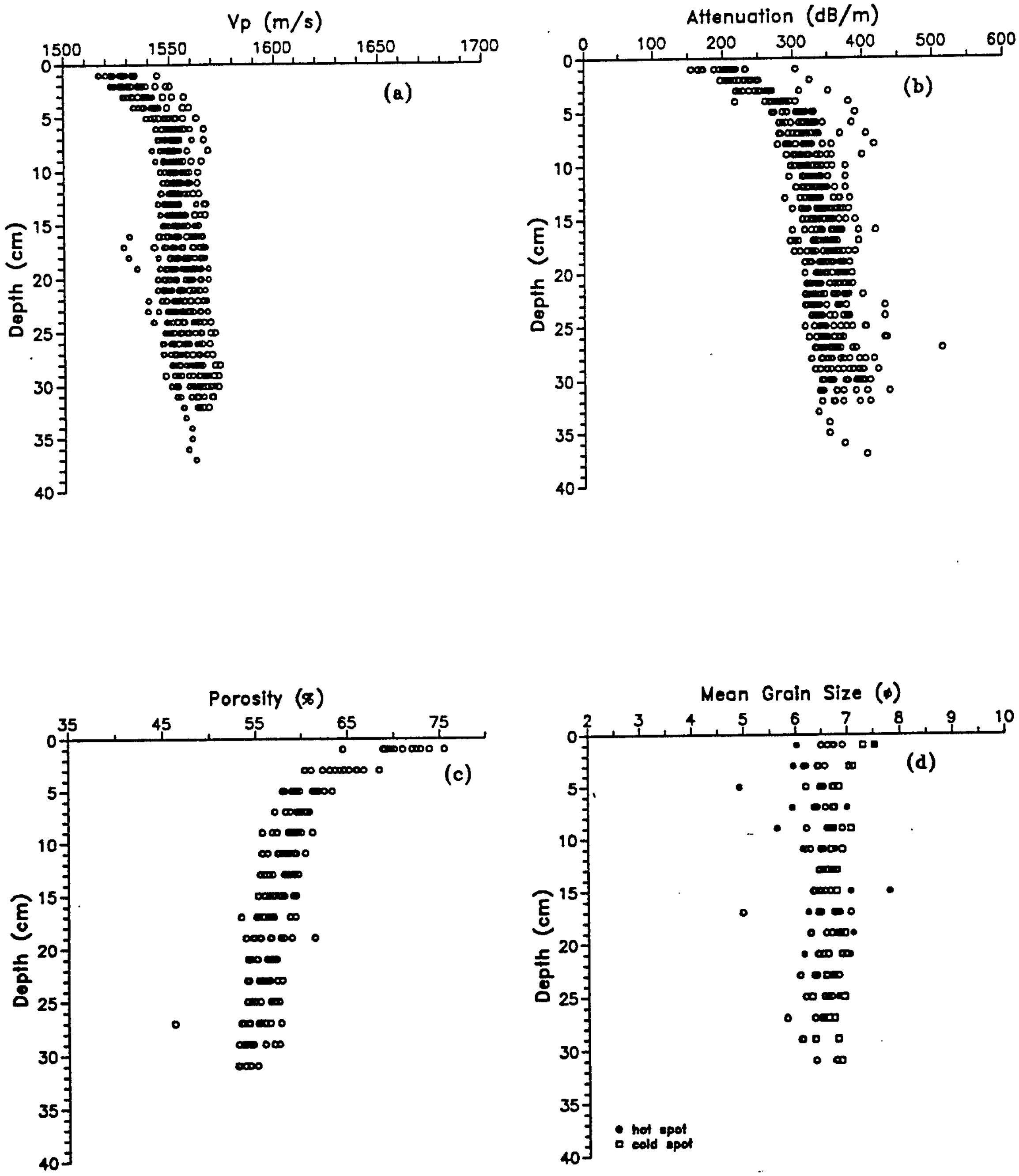

Fig. 9. Depth profiles of (a) compressional wave velocity, (b) compressional wave attenuation, (c) porosity and (d) mean grain size in sediment from the Dry Tortugas site.

2.4 Effects of Carbonate Dissolution and Precipitation on Sediment Physical Properties and Structure: Microfossils Component (Principal Investigator: C.A. Brunner)

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PROJECT OBJECTIVES

This report describes the activities of the first 6 months of this contract, which began April 13, 1995. The objectives of the three year contract are to assess and quantify effects of organic matter oxidation on the solid constituents of sediment cores, with particular focus on foraminiferal tests as an indicator of general sediment condition. Effects include dissolution of carbonate tests, precipitation of calcium carbonate in test interiors and host sediment, and growth of pyrite or manganese oxides. Results will be compared to reactions predicted from pore water chemistry done on identical core samples under a separate contract to Dr. Alan Shiller of USM.

INTRODUCTION

Oxidation of organic matter is an important process in surface sediments of the Tortugas region, based on preliminary data (Shiller et al., 1995). Early diagenesis of organic matter proceeds through a sequence of reducing reactions described by Froelich et al. (1979). The reactions include reduction by bacterial respiration of oxygen followed by manganese oxide, nitrate, iron oxides, and sulfate. Some of these reactions produce protons, which promotes the dissolution of a carbonate, and other reactions consume protons, which promotes carbonate precipitation. The resultant dissolution and cementation could significantly affect the acoustic properties of sediment, and so study of early diagenesis is relevant to the CBBL project.

SOLID PRODUCTS OF ORGANIC CARBON DIAGENESIS

Benthic foraminifers are important constituents of sediments in the near-reef environment. They form a significant proportion of the sediments in the Dry Tortugas region, comprising about 12% of the particles in the sand-size fraction (Orsi et al., in prep.). Foraminifer tests may play an interesting and important role in early diagenesis of carbonate sediment in the region for two reasons. (1) The chambered tests enclose a chemical micro-environment that is isolated from surrounding pore waters and matrix except for restricted access through narrow apertures, canals, and small pores. The test interiors of the diverse fauna (more than 78 species noted to date) offer a variety of shapes and different-sized spaces, which may promote dissolution or precipitation of carbonate and other solid products of oxidation and reduction such as manganese oxide and iron sulfide. (2) Tests of different suborders are made of different forms of calcium carbonate, including high and low magnesian calcite and aragonite.

These different phases have different solubilities, and their surfaces affect precipitation in different ways.

I proposed the following questions. 1) *Do foraminiferal tests harbor indications of early diagenesis due to oxidation of organic matter in a pattern consistent with the pore water chemistry?* 2) *Does the reduction sequence in the sediment column occur in test interiors sooner (e.g., at a shallower depth) than in the matrix hosting the tests due to formation of chemical micro-habitats in test interiors?* 3) *Does test composition promote or retard precipitation?*

FOSSIL ASSEMBLAGE INDICATES DEGREE OF REDUCTION

Fossil assemblage composition may also provide clues to the degree of reduction in the sediments. Specifically, a foraminiferal indicator - or proxy - of reduction may be feasible because of the different lifestyles of various taxa. Benthic foraminifers can be divided into two groups: (1) those that live as infaunal dwellers and (2) those that live at the surface or external to the sediment. The infauna are generally motile and actively burrow through the sediment (Kitazato, 1984, 1988a, and 1988b). They must extract oxygen from pore waters in order to survive, and so are very dependent on the diagenesis that controls oxygen concentrations. The idea that benthic foraminifer distributions are sensitive to oxygen concentrations and pore water chemistry is not new. The literature is filled with reports of species with a preference for the oxygen minimum on continental margins (Quinterno and Gardner, 1987; Mullins et al., 1985; Bernhard, 1993; many others). Corliss and Emerson (1990 and subsequent papers) report that the benthic foraminiferal infauna is segregated into shallow and deep depth preferences depending on the depth of the oxic layer.

In contrast, the extra-sediment taxa live as sessile, motile, or partially motile forms on a variety of surfaces (Kitazato, 1988b). The surfaces include hard rock, rubble or reef substrates, plants such as macroalgae and sea grasses; and even structures they build themselves to stand above the sediment (Altenbach et al., 1993). For my purposes, I will include those that dwell on the sediment surface in the extra-sediment group in our study region. All of the extra-sediment forms in the study region extract their oxygen from well-oxygenated bottom waters and avoid the competition for oxygen that occurs in the sediments.

I propose using faunal proportions as proxies of oxidation intensity. The numbers of infaunal species relative to extra-sediment species and the proportion of shallow- to deep-dwelling infauna will reflect the depth and degree of oxygenation in the sediment. The proxies can be tested in the cores where pore water data is available and applied to long gravity cores to assess the history of organic carbon diagenesis in the region.

RESULTS OF PAST 6 MONTHS

Do foraminiferal tests harbor indications of early diagenesis due to oxidation of organic matter in a pattern consistent with the pore water chemistry? Foraminifers from 1-cm thick slices

throughout the cores were mounted for SEM analysis from box cores, 181 and 185. To date, all of the slices from core 185 have been examined in detail.

Distinct zonations in carbonate dissolution and precipitation were noted with depth in core 185. Unit 1: Foraminifers were generally well preserved in the 0-1 and 1-2 cm slices with no evidence of dissolution or precipitation. Foraminifer preservation was degraded by extensive bioerosion of both infaunal and epiphytic tests probably by boring algae (Sally Walker, pers. com., 1995). The bore holes were typically 5 to 8 μm in diameter. Pyrite framboids were present in tests and quite rare in the bounding sediment matrix. Unit 2: Foraminifer tests harbor aragonite formation in the intervals from 2 to 5 cm. Radiating aragonite (?) crystal masses 15 to 18 m in diameter were observed in the sediment filling test chamberlets. In one specimen at 2-3 cm, aragonite crystals were clearly attached to the chamber walls, and a web of crystals infilled several chamberlets of a high magnesian foraminifer. Pyrite occurred rarely in both tests and in the bounding sediment matrix. Unit 3: The interval from 5 to 11 cm contains foraminifers affected by dissolution expressed as widening of algal bore holes, merging of algal bore holes, removal of chamberlet walls, roughening of wall surfaces, and irregularity of chamberlet shapes. Pyrite was much more abundant in tests than in the overlying units. It was also measurably more abundant in the bounding sediment matrix. Unit 4: The interval from 11 to 13 and 17 to 19 cm contained evidence of aragonite precipitation in contrast to the intervening intervals, which showed distinct dissolution. Pyrite was as abundant in both tests and matrix as in Unit 3. The results described from Units 1-3 are consistent with expectations of organic matter digestion and the preliminary oxygen data obtained by microelectrode profiling of the upper centimeter. The results from Unit 4 require further explanation when pore water data are available for comparison.

I propose using faunal proportions as proxies of oxidation intensity. A census of foraminiferal species in 181 and 185 has begun. Specimens are currently being picked from prepared samples. A census from core-top material studied during the pilot program (Orsi et al., in prep.) shows that the fauna is dominated by epiphytes and other extra-sediment foraminifers. Only one infaunal taxon was identified, a genus known for its tolerance of low oxygen conditions, *Nonionellina* (Corliss and Emerson, 1990).

PRELIMINARY CONCLUSIONS

The sequence of preservation states of foraminiferal tests and the abundance of pyrite with increasing depth in core follows predictions based on a general model of organic carbon oxidation in surficial sediments (Froelich et al., 1979). The surface layer shows no clear signs of either dissolution or precipitation, but succeeding intervals show a zone of carbonate precipitation underlain by a zone of carbonate dissolution. We hypothesize that the upper layer coincides with the interval where bacteria respire oxygen; the zone of carbonate precipitation coincides with utilization of manganese oxides, nitrate, and iron oxides; and the zone of dissolution coincides with utilization of sulphate. This will be tested by analysis of pore water chemistry by Dr. Alan Shiller in a separate and co-ordinated contract. The pattern of preservation with depth will be verified in additional cores, and patchiness of the phenomena will be considered..

The result is significant to CBBL because it shows that organic carbon oxidation in surficial sediments drives an intricate sequence of both dissolution and precipitation of carbonate, which can greatly affect acoustic properties.

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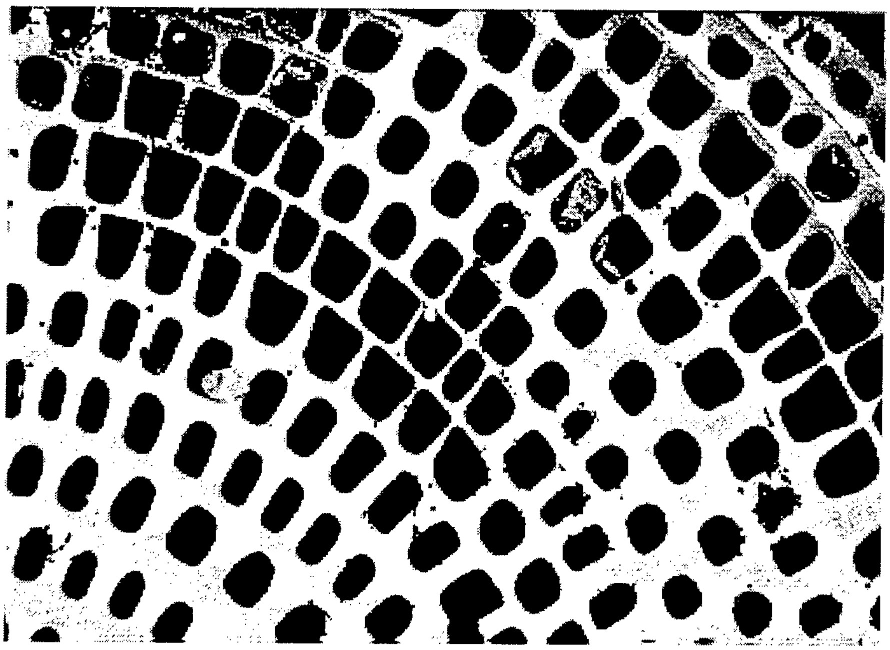

FIGURE 1. An example of a well preserved benthonic foraminifer (*Parasorites orbitiloides*, x200) from Unit 1. Note that the surfaces of the chamberlet walls are smooth and that algal boring of wall interiors is minimal. The polished section is imaged by backscattered electrons.

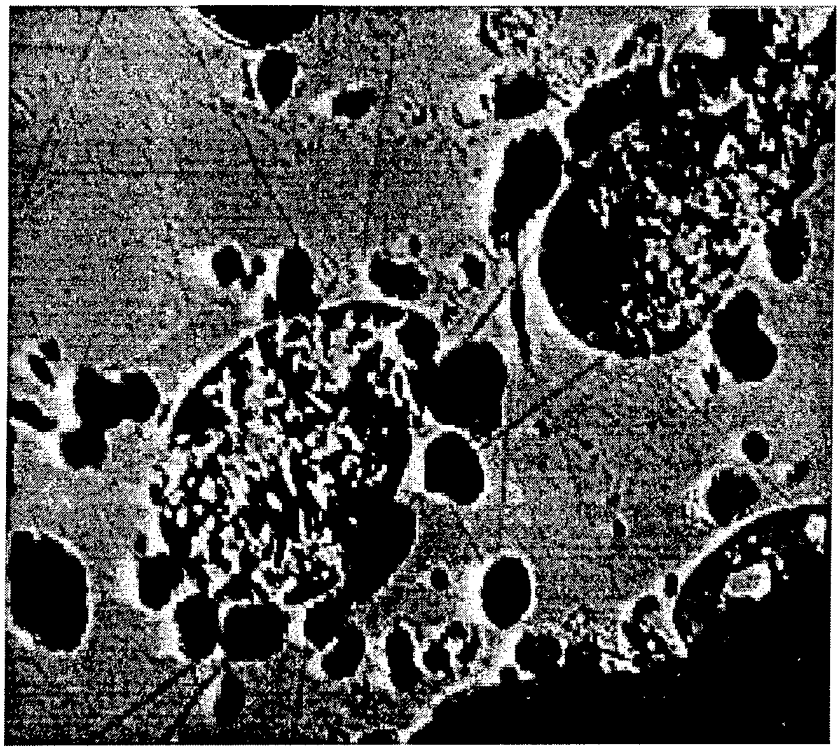

FIGURE 2. A benthonic foraminifer (*Archaias angulatas,* x1000) from box core 185, 2-3 cm shows evidence of carbonate precipitation that characterizes Unit 2. Note that calcium carbonate (aragonite?) needles fill two chamberlets. Note also the small holes 5 to 10 micrometers in diameter made by boring algae. The section is imaged by backscattered electrons.

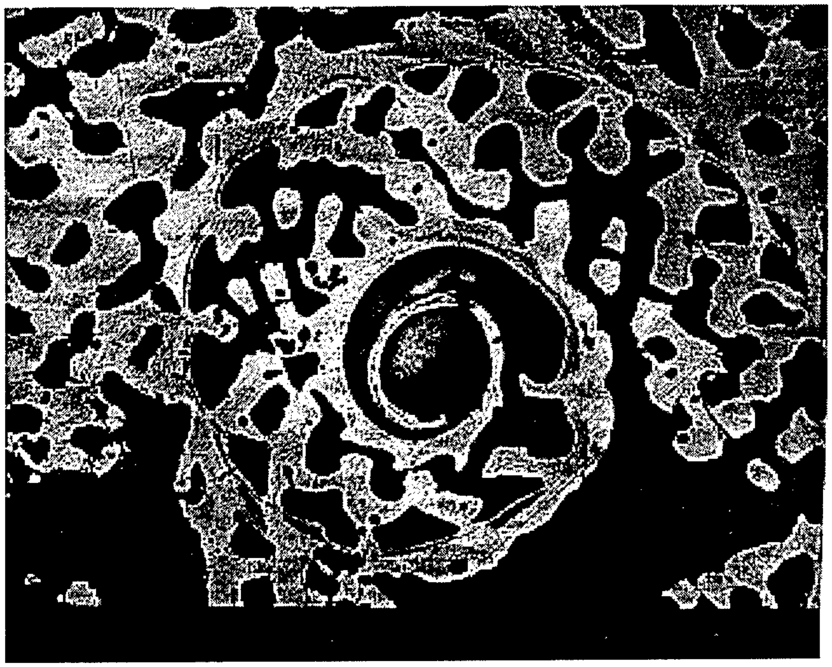

FIGURE 3. A benthonic foraminifer (*Archaias angulatas,* x200) from box core 185, 5-6 cm shows evidence of dissolution that characterizes Unit 3. Dissolution features include algal borings that have been enlarged by chemical dissolution, chamberlet walls that are breached, angular chamberlet shapes, and rough chamberlet surfaces. The section is imaged by back-scattered electrons.

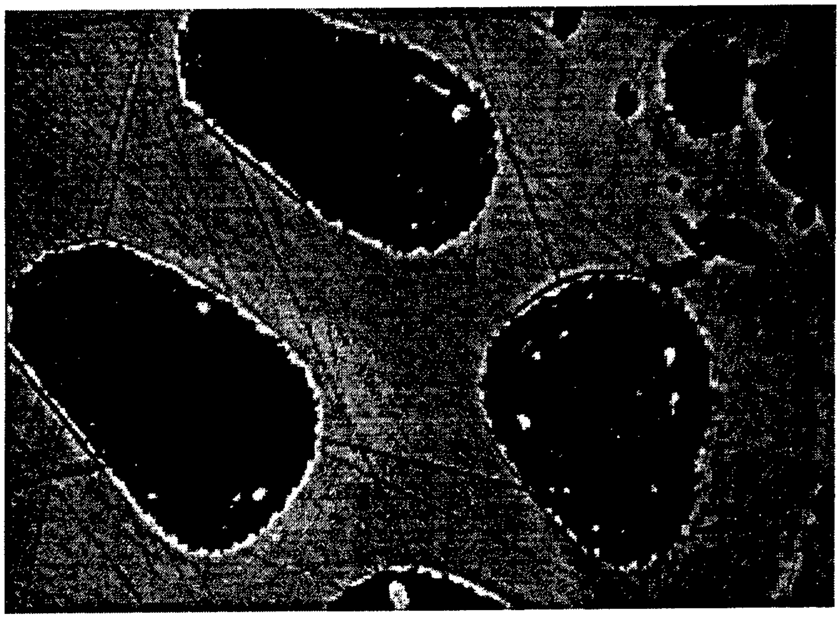

FIGURE 4. A benthonic foraminifer (*Cyclorbitiloides* sp., x1000) from box core 185, 11-13 cm in Unit 4 shows evidence of calcium carbonate (aragonite?) precipitation in the form of a rind lining the inner surfaces of the chamberlet walls. The polished section is imaged by backscattered electorns.

2.5 Processes of Macro Scale Volume Inhomogeneity in the Benthic Boundary Layer (Principal Investigators: W.R. Bryant and N.C. Slowey)

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PROJECT GOALS

The goals of this project has been to understand how and why the physical properties and the geology of the boundary layer vary in terms of time dependent physical, biological and chemical processes within various shallow water geological environments. Specifically, we are investigating the geotechnical stratigraphy, which includes the density, shear strength (cohesion), porosity, saturation (gas) and sediment and biological component distribution and their three-dimensional structural arrangement, within the boundary layer in more detail that has previously been possible. These studies will lead to a description of boundary layer gradients of density, porosity and cohesion and their relation to time, sediment type and structural arrangement and states of stress as defined by in situ pore pressure measurements. In addition to sediments of a cohesive nature (clays and silts, clayey sands and sandy clays), fine-grained carbonate sediments are also being investigated. The measurements of the density, shear strength (cohesion) and compressibility will supply the parameters necessary for determining the bearing capacity and long-term stability of objects placed in or near the boundary layer. The knowledge gained with help generate the physical and numerical models that predict the penetration and stability of objects on the seafloor, supply data for models of the geoacoustic nature of the boundary layer and arrive at realistic measures of sediment micro and macrostructural volume inhomogeneity that can be applied to geo- and seismo-acoustic problems.

This report reviews our goals, efforts and accomplishments during the first three years of the CBBL Research Program. Our research is based on the premise that the fundamental properties which control both the mechanics of objects and the propagation of compressional waves at the seafloor include the bulk density, shear strength and compressibility of sediments. For this reason, the success of efforts to predict the location of objects and then acoustically detect them depends upon our understanding of the spatial and temporal variability of these properties. The largest changes of the bulk density, shear strength and compressibility of sediments within most marine environments typically occur within the upper few meters of the seafloor (the boundary layer). We believe these changes are closely coupled with variations in the texture and structure of sediments. Based on this hypothesis, we have investigated the spatial variability of the physical and geological properties, and the structure of sediments within the boundary layers of select marine environments. Our specific goals were to characterize this variability (especially vertical gradients) in greater detail than before possible to determine how the variability in one

property relates to that in others. With the aid of other CBBL investigators, our general aim is to understand how and why variations in seafloor sediment characteristics arise from the dominant physical, biological and chemical processes within the benthic boundary layer.

INTRODUCTION

During the last three years, we have put forth considerable effort on behalf of these aims. Much necessary time has been spent organizing, testing equipment, staging and participating in the Eckernförde Bay, Panama City and Key West field efforts, making measurements in the laboratory, analyzing data, and interacting with other project members. For example, aside from daily CBBL activities at Texas A&M, members of our group have spent 85 man-days in meetings and over 520 man-days working in the field on behalf of the CBBL Research Program. The rewards for these efforts are severalfold: we have successfully collected a large number of samples to help us achieve our goals, we have completed analysis of a significant portion of them, we have successfully tested coring devices and collected samples on behalf of several other CBBL investigators, and we have initiated several close collaborations with other investigators to achieve general CBBL objectives.

STUDY AREAS

Eckernförde Bay Gassy Sediment Study Site

We collected a suite of gravity cores and box core subcores containing cohesive sediments from the Eckernförde Bay, Germany during February and May of 1993 (Table 1), and during June of 1994 (Table 2). To examine sediment property variability over both macro-scale (mm's to cm's) and micro-morphologic (m's to 100 m's) spatial scales, we are comparing measurements made in the following ways: (1) along transects that extend both horizontally and with depth within individual cores, (2) between gravity cores from the same site and between subcores from the same box core, and (3) between regularly spaced cores from the same general study area. We have determined the following sediment properties: bulk density, compressional wave velocity, water content, porosity, shear strength and, in some cases, magnetic susceptibility, at spatial intervals of 0.5 to 2.0 cm. Stereo X-radiographs of whole cores and slabs of longitudinally-split cores are used as indicators of sediment structure. Grain size, grain density, mineralogy and other measurements are also being made at select intervals. These measurements were made using a multi-sensor core logger, Swedish fall cone, vane shear device, discretely sampled volumes of sediment, pipette analysis, air-compression pycnometer,

Table 1a. Status of Analyses of 1993 Baltic Sea 12.5-cm Diameter Gravity Core

Core ID	Length (cm)	X-ray	BD	WC	Por	SS
0008 BSGC	500	Y	Y	Y	Y	Y
0009 BSGC	500	Y	Y	Y	Y	Y
0010 BSGC	335	Y	Y	Y	Y	Y
0020 BSGC	400	Y	Y	Y	Y	Y
0021 BSGC	218	Y	Y	Y	Y	Y

0022 BSGC	300	Y	Y	Y	Y	Y
0023 BSGC	400	Y	Y	Y	Y	Y
0026 BSGC	500	Y	Y	Y	Y	Y
0028 BSGC	350	Y	Y	Y	Y	Y
0030 BSGC	249	Y	Y	Y	Y	Y
0033 BSGC	247	Y	Y	Y	Y	Y

Table 1b. Status of Analyses of 1993 Baltic Sea Box Sub-Cores

Core ID	Length (cm)	X-Ray	GD	BD	VP	WC	Por	SS
0035 BSBC	44	Y	Y	Y	Y	Y	Y	Y
0036 BSBC	~50	Y	Y	Y	Y	Y	Y	Y
0037 BSBC	~50	Y	Y	Y	Y	Y	Y	Y
0039 BSBC	~50	Y	Y	Y	Y	Y	Y	Y
0041 BSBC	~50	Y	Y	Y	Y	Y	Y	Y
0042 BSBC	~50	Y	Y	Y	Y	Y	Y	Y
0048 BSBC	~50	Y	Y	Y	Y	Y	Y	Y
0052 BSBC	26	Y	Y	Y	Y	Y	Y	Y

Table 1c. Status of Analyses of 1993 Baltic Sea 10-cm Diameter Gravity Cores

Core ID	Length (cm)	X-Ray	GD	BD	VP	WC	Por	SS
0206 BSGC	185	Y	Y	Y	Y	Y	Y	Y
0207 BSGC	200	Y	Y	Y	Y	Y	Y	Y
0208 BSGC	170	Y	Y	Y	Y	Y	Y	Y
0217 BSGC	189	Y	Y	Y	Y	Y	Y	Y
0218 BSGC	160	Y	Y	Y	Y	Y	Y	Y
0219 BSGC	180	Y	Y	Y	Y	Y	Y	Y
0220 BSGC	165	Y	Y	Y	Y	Y	Y	Y
0306 BSGC	192	Y	Y	Y	Y	Y	Y	Y
0308 BSGC	193	Y	Y	Y	Y	Y	Y	Y
0311 BSGC	184	Y	Y	Y	Y	Y	Y	Y
0316 BSGC	166	Y	*	Y	*	Y	Y	Y
0317 BSGC	180	Y	Y	Y	Y	Y	Y	Y
0320 BSDC	170	Y	Y	Y	Y	Y	Y	Y
0321 BSGC	170	Y	Y	Y	Y	Y	Y	Y
0326 BSGC	146	Y	Y	Y	Y	Y	Y	Y
0327 BSGC	122	Y	Y	Y	Y	Y	Y	Y
0330 BSGC	218	Y	*	Y	*	Y	Y	Y
0331 BSGC	215	Y	Y	Y	Y	Y	Y	Y
0332 BSGC	175	Y	*	Y	*	Y	Y	Y
0334 BSGC	217	Y	*	Y	*	Y	Y	Y
0336 BSGC	200	Y	Y	Y	Y	Y	Y	Y
0337 BSGC	210	Y	Y	Y	Y	Y	Y	Y
0338 BSGC	163	Y	Y	Y	Y	Y	Y	Y

Table 2. Status of Analyses of 1994 Baltic Sea 12.5-cm Diameter Gravity Cores

Core ID	Length (cm)	X-Ray	BD	WC	Por	SS
624 BSGC	431	Y	Y	Y	Y	Y
625 BSGC	477	Y	Y	Y	Y	Y
626 BSGC	460	Y	Y	Y	Y	Y
627 BSGC	472	Y	Y	Y	Y	Y
628 BSGC	415	Y	Y	Y	Y	Y

Key: X-Ray = Stereo X-radiographs
GD = Bulk Density based on weight and volume measured of discrete samples
BD = Bulk Density based on Gamma ray attenuation
VP = P-Wave Velocity
WC = Water Content
Por = Porosity
SS = Shear Strength
* = no measurements as pressure and water lost from cores due to leaking caps

X-ray diffractometer, etc. Though tedious, these determinations are now completed, allowing the focus of our efforts with regard to these samples to shift from analysis to interpretation.

As the primary basis of his Ph.D. dissertation, Tiesong. Lu, a graduate student at Texas A & M, is using statistical techniques such as multiple regression analysis to investigate correlations among the physical, geotechnical and geoacoustic properties of the sediments of Eckernförde Bay and other regions where gassy sediments exist. The goal is to understand controls of compressional wave velocity and shear strength. An evaluation/comparison of vane shear and fall cone shear strength measurements was made and a paper has been submitted to a geotechnical journal. Table 3 is a set of predictor equation relating shear strength (SS) with depth below the seafloor for various locations and cores in Eckernförde Bay. Most of these equations are valid for sediment below 50 cm subbottom. For the immediate surface sediments (0-50 cm) one is refer to the box core equations. Certain sections of the Bay, such as along Lambert's Line, the shear strength of the sediment are very consistent between cores and the lines of best fit have a very high degree of correlation (R^2=.93 to .96).

Table 3: Predictor Equations for Shear Strength

	Lambert's Line (50 to 500 cm)	
Core 625	SS= 1.76 + 0.0231 Depth (cm)	R^2 =.93
Core 626	SS= 1.03 + 0.0226 Depth (cm)	R^2 =.96
Core 627	SS= 1.53 + 0.0215 Depth (cm)	R^2 =.95
Core 628	SS= 3.45 + 0.0262 Depth (cm)	R^2 =.96
General Area	**SS= 2.01 + 0.0240 Depth (cm)**	$\mathbf{R^2}$ **=.95**

Lamberts Line (50 to 200 cm)

Core 331	SS= 0.685 + 0.0325 Depth (cm)	R^2 =.73
Core 335	SS= 1.011 + 0.0162 Depth (cm)	R^2 =.93
Core 336	SS= 1.241 + 0.0238 Depth (cm)	R^2 =.95
Core 337	SS= 1.241 + 0.0238 Depth (cm)	R^2 =.95

Box Cores Within Stanic Tower Square (0 to50cm)

Core 42-1A	SS= 0.246 + 0.0323 Depth (cm)	R^2 =.53
Core 42-1B	SS= 0.217 + 0.0505 Depth (cm)	R^2 =.83
Core 42-2A	SS= 0.280 + 0.0346 Depth (cm)	R^2 =.88
Core 42-2B	SS= 0.207 + 0.0252 Depth (cm)	R^2 =.56
Core 39-1A	SS= 0.319 + 0.0224 Depth (cm)	R^2 =.56
Core 39-1B	SS= 0.360 + 0.0324 Depth (cm)	R^2 =.61
General Area	**SS= 0.272 + 0.0329 Depth (cm)**	**R^2 =.66**

Box Core Within Pockmark (0 to 50cm)

Core 48	SS= 3.178 - 0.0586 Depth (cm)	R^2 =.54

Eckernförder Bay

Core 9	SS= 1.581 + 0.0319 Depth (cm)	R^2 =.95
Core 20	SS= 1.554 + 0.0212 Depth (cm)	R^2 =.97
Core 21	SS= 4.279 + 0.00331 Depth (cm)	R^2 =.45
Core 22	SS= 0.321 + 0.0244 Depth (cm)	R^2 =.95
Core 23	SS= 0.808 + 0.0148 Depth (cm)	R^2 =.90
Core 26	SS= 0.349 + 0.0221 Depth (cm)	R^2 =.94
Core 28	SS= 0.611 + 0.0145 Depth (cm)	R^2 =.96
Core 30	SS= 1.926 + 0.0108 Depth (cm)	R^2 =.89
Core 33	SS= 0.935 + 0.0194 Depth (cm)	R^2 =.93
Core 37	SS= 0.858 + 0.00259 Depth (cm)	R^2 =.75
Core 52	SS= 1.809 + 0.0139 Depth (cm)	R^2 =.92
Core 206	SS= 1.174 + 0.0196 Depth (cm)	R^2 =.98
Core 207	SS= 0.493 + 0.0268 Depth (cm)	R^2 =.98
Core 208	SS= 1.361 + 0.0258 Depth (cm)	R^2 =.98
Core 217	SS= 0.769 + 0.0314 Depth (cm)	R^2 =.99
Core 218	SS= 1.235 + 0.0263 Depth (cm)	R^2 =.99
Core 219	SS= 0.751 + 0.0285 Depth (cm)	R^2 =.99
Core 220	SS= 0.825 + 0.0288 Depth (cm)	R^2 =.95
Core 306	SS= -0.414 + 0.0303 Depth (cm)	R^2 =.95

Stoll's Line

Core 624	SS= 2.27 + 0.0268 Depth (cm)	R^2 =.97

Stereo X- radiographs are being catalogued by determining the specific location of all major and minor structural elements such as silt layers, gassy sediments, shell layers (including size,

orientation and number), and quantitative estimates of sediment density variability (magnitude and spatial dimensions). These measurements will be correlated with the high-resolution vertical incidence and side-scan sonar data collected by other investigators. It is our contention that structural features such as shell layers and gas concentrations are expressed in the high-resolution records. Shell layers in particular are a feature that has been generally ignored. But, since shell layers can both reflect and scatter sound, their geoacoustic impact may in some cases be greater than changes in sediment type or density. Shell layers may be a prime source for the production of reflectors observed on high-resolution seismic profiles.

The data resulting from the analysis of the 2 to 5 meter-long gravity cores taken with the Kiel Core in Eckenförde are of particular significance in that they offer excellent ground-truthing for the various seismic techniques. We are fortunate that two different sediment classification systems have been used and both systems use multi-frequencies. It offers us a unique opportunity to determine specific causes and conditions of reflections, a subject that has been examined many times but one that when dealing with fine-grained sediments alludes us. If reflections occur at intervals not defined by velocity, density or structural changes their existence is of extreme importance because it indicates either a weakness in our understanding of geoacoustic wave propagation or that the instrumentation is lousy (which is usually the case).

We expect that analysis of the CBBL data will lead to publications about benthic boundary layer sediments which are focused on the following themes:

- detailed relationships and macro-scale variability among the geologic, physical and acoustic properties of the upper 0.5 m of the seafloor

- consideration of sediment property variability in the upper 2 to 5 m of the seafloor, including time-series analysis of compressional wave velocity and bulk density data to quantify and statistically characterize both macro-scale and micro-morphologic variability

- utilization of stereo X-radiographs to consider the genesis and macro and micro characteristics of sediment structure and its influence on other properties.

To fully achieve our specific goals and broader CBBL aims, we are working together with other CBBL investigators. During the February, 1993, survey cruise, we tested and evaluated coring equipment on behalf of all investigators and helped geologically interpret the profiles collected during vertical incidence and side-scan sonar surveys. During the May, 1993, and June, 1994, cruises, we collected cores on behalf of groups led by A. Anderson of TAMU, C. Martens of UNC, A. Silva of URI, and D. & D. Lavoie and M. Richardson of NRL. We are working jointly with other investigators in several areas, the following are the primary collaborations: with A. Davis of Wales, D Lambert of NRL and S. Schock of FAU to ground-truth and geologically interpret normal incidence seismic reflection data; with A. Silva of URI to investigate sediment geotechnical properties; with R. Stoll of LDEO to relate shear strength to shear wave velocities; with C. Nittrouer and his group to interpret sediment stratigraphy in terms of the history of environmental processes; with D. Young and R. Holyer of NRL to digitally analyze stereo X-radiographs for sediment structure; and with R. Faas of Lafayette University to study the time-

dependent physical and acoustic properties of fluid made through laboratory experiments. These and other efforts have lead and will lead to a number of joint publications in peer-reviewed journals, including several in the special volumes of the journals Geo-Marine Letters and Estuarine, Coastal and Shelf Science.

Panama City Shelf Sands Study Site

Members of our small group served the overall aims of the CBBL Research Program in several ways during the August 1994 cruise off of Panama City. We helped make arrangements for the RV GYRE and coring equipment, we acted in the capacity of co-chief scientists to coordinate and satisfy the logistical needs of other investigators, and we contributed to NRL diving operations. During the cruise, members of our team also obtained a suite of ~90 Shipek grab samples and some short cores for our own research needs.

We suspect that variability in physical and acoustic properties and side-scan sonar character of the sandy Panama City sediments reflect changes in the size, shape and packing of sediment grains at the sediment water interface. We have following several approaches to test this hypothesis. First, we determined the grain-size and carbonate content of the surficial sediments and investigated how their variations throughout the study site relate to side-scan sonar images and digital backscatter data. This work is being done together with I. Stender and his group from FWG. It is completed and a manuscript submitted for publication. In the next two years, we intend on investigating the relationships between surficial sediment properties and the amplitude of surface reflections measured during lower-frequency, high-resolution vertical incidence seisimic profiling of study site. This work will be pursued together with S. Schock of FAU and D. Lambert of NRL.

Key West Carbonate Sediment Study Site

A member of our group participated on the 1994 site survey cruise to the Florida Keys in order to assist NRL investigators. Exploratory samples were collected including 4 diver cores and 35 Smith-MacIntyre grab samples from the study areas off the Marquesas Keys and the Dry Tortugas. Bulk density, compressional wave velocity and CAT scan data have been collected from the diver cores in the same fashion as described above for the cores collected in Panama City. In February, 1995, six members of Texas A&M participated in the Key West experiment in which seventy 4 inch diameter gravity cores were recovered from the Marquesas and Dry Tortugas areas (Table 4). We logged all of these cores (124.5 meters) at a 1 cm interval for velocity and bulk density at the Key West laboratory. Thirty-five of the cores were returned to Texas A&M and thirty-five were sent to the University of Rhode Island. Nine vibracores were recovered and velocity and density will be determined. We also logged 35 cores for velocity and density for NRL (Dawn Lavoie).

Table 4. Key West Gravity Cores

Core ID	Length (cm)	Latitude (N)	Longitude (S)	Water (m)	Disposition
KW-SJ-GC-166	163	24°49.991'	82°12.052'	22.0	URI
KW-SJ-GC-167	208	24°45.090'	82°11.420'	22.0	URI
KW-SJ-GC-168	216	24°44.934'	82°10.943'	22.0	URI
KW-SJ-GC-169	240	24°45.116'	82°10.902'	22.3	TAMU
KW-SJ-GC-170	220	24°44.991'	82°11.813'	23.2	TAMU
KW-SJ-GC-171	237	24°43.693'	82°12.001'	21.4	URI
KW-SJ-GC-173	137	24°43.731'	82°11.018'	21.5	TAMU
KW-SJ-GC-175	277	24°41.197'	82°11.048'	19.4	URI
KW-SJ-GC-176	298	24°41.224'	82°12.022'	18.2	TAMU
KW-SJ-GC-177	272	24°42.514'	82°12.054'	20.1	TAMU
KW-SJ-GC-178	267	24°42.490'	82°11.551'	20.1	URI
KW-SJ-GC-180	273	24°42.507'	82°11.547'	19.9	TAMU
KW-SJ-GC-181	263	24°42.566'	82°11.026'	20.9	URI
KW-SJ-GC-182	278	24°42.883'	82°11.018'	20.7	URI
KW-SJ-GC-186	228	24°42.244'	82°11.289'	22.0	TAMU
KW-SJ-GC-187	239	24°40.715'	82°12.013'	19.4	TAMU
KW-SJ-GC-188	250	24°40.725'	82°12.047'	19.6	URI
KW-SJ-GC-189	237	24°40.668'	82°11.486'	18.0	TAMU
KW-SJ-GC-190	233	24°40.682'	82°11.019'	17.5	URI
KW-SJ-GC-191	234	24°40.711'	82°11.017'	17.6	TAMU
KW-SJ-GC-192	298	24°41.212'	82°11.501'	18.6	URI
KW-SJ-GC-194	190	24°43.793'	82°11.544'	20.9	TAMU
KW-SJ-GC-197	245	24°42.033'	82°04.535'	16.1	TAMU
KW-SJ-GC-198	139	24°42.866'	82°04.437'	19.2	URI
KW-SJ-GC-199	114	24°44.462'	82°04.418'	21.3	TAMU
KW-SJ-GC-201	135	24°44.601'	82°06.801'	22.0	URI
KW-SJ-BC-204	18	24°42.485'	82°11.511'	19.7	TAMU
KW-SJ-GC-213	269	24°45.113'	82°14.950'	23.3	URI
KW-SJ-GC-214	160	24°36.495'	82°50.919'	27.1	URI
KW-SJ-GC-217	138	24°36.331'	82°50.765'	26.5	TAMU
KW-SJ-GC-219	62	24°36.393'	82°50.398'	26.0	TAM
KW-SJ-GC-221	65	24°36.075'	82°50.214'	25.0	TAMU
KW-SJ-GC-224	66	24°36.064'	82°50.778'	26.9	TAMU
KW-SJ-GC-226	37	24°35.910'	82°51.134'	27.9	URI
KW-SJ-GC-227	161	24°35.768'	82°51.018"	27.8	TAMU
KW-SJ-GC-230	197	24°35.885'	82°50.734'	26.8	URI
KW-SJ-GC-232	67	24°35.808'	82°50.457'	25.7	URI
KW-SJ-GC-233	171	24°36.747'	82°51.038'	26.0	TAMU
KW-SJ-GC-234	201	24°36.932'	82°51.080'	25.7	URI
KW-SJ-GC-236	225	24°36.929'	82°50.825'	25.1	TAMU
KW-SJ-GC-238	145	24°36.892'	82°50.256'	25.3	TAMU
KW-SJ-GC-239	101	24°36.631'	82°50.448'	26.7	URI

KW-SJ-GC-241	190	24°36.462'	82°50.796'	26.3	URI
KW-SJ-GC-255	55	24°34.538'	82°50.554'	23.9	TAMU
KW-SJ-GC-256	199	24°37.095'	82°50.481'	24.8	TAMU
KW-SJ-GC-257	134	24°37.006'	82°50.399'	25.0	URI
KW-SJ-GC-262	200	24°34.478'	82°50.517'	28.7	TAMU
KW-SJ-GC-263	125	24°34.478'	82°51.517'	28.7	TAMU
KW-SJ-GC-269	122	24°34.464'	82°49.487'	29.0	URI
KW-SJ-VC-273	55	24°30.208'	82°29.005'	18.9	TAMU
KW-SJ-VC-275	80	24°30.202'	82°28.996'	18.8	TAMU
KW-SJ-VC-277	66	24°30.274'	82°20.153'	19.8	TAMU
KW-SJ-VC-278	90	24°31.582'	82°29.378'	11.0	TAMU
KW-SJ-VC-281	75	24°31.545'	82°29.381'	11.9	TAMU
KW-SJ-VC-282	50	24°35.460'	82°28.370'	16.6	TAMU
KW-SJ-GC-283	198	24°44.012'	82°26.415'	26.0	TAMU
KW-SJ-GC-285	161	24°36.473'	82°51.505'	26.4	URI
KW-SJ-GC-287	92	24°34.478'	82°52.000'	27.9	TAMU
KW-SJ-GC-288	76	24°35.383'	82°51.650'	29.2	URI
KW-SJ-GC-289	156	24°36.035'	82°51.475'	27.8	TAMU
KW-SJ-GC-290	166	24°36.974'	82°51.524'	24.7	URI
KW-SJ-GC-293	138	24°36.344'	82°52.069'	24.7	URI
KW-SJ-GC-294	140	24°35.999'	82°52.000'	26.5	TAMU
KW-SJ-GC-295	120	24°35.526'	82°50.988'	27.4	URI
KW-SJ-GC-296	137	24°36.054'	82°50.994'	27.5	TAMU
KW-SJ-GC-301	105	24°36.330'	82°50.454'	26.3	URI
KW-SJ-VC-302	43	24°24.354'	82°50.490'	25.1	TAMU
KW-SJ-VC-304	78	24°36.030'	82°49.908'	24.7	TAMU
KW-SJ-VC-307	73	24°35.994'	82°49.476'	24.9	TAMU
KW-SJ-GC-308	152	24°36.678'	82°50.592'	25.6	TAMU
KW-SJ-GC-309	158	24°36.978'	82°50.688'	24.9	URI
KW-SJ-GC-310	158	24°36.678'	82°50.718'	25.9	URI
KW-SJ-GC-311	201	24°36.690'	82°50.754'	25.8	TAMU
KW-SJ-GC-312	193	24°36.672'	82°50.652'	26.0	TAMU
KW-SJ-GC-313	201	24°36.726'	82°50.658'	25.8	URI
KW-SJ-GC-317	245	24°36.714'	82°50.805'	26.2	URI
KW-SJ-GC-320	190	24°36.828'	82°50.886'	25.7	TAMU
KW-SJ-GC-321	164	24°36.816'	82°50.922'	25.8	URI
KW-SJ-GC-326	295	24°43.984'	82°26.466'	26.0	URI

Key West Cores - Methods and Results

We suspect that under the influence of hydrodynamic forces at the study site, the nonspherically shaped biogenic sediment grains may well become preferentially orientated with the sediments at the seafloor. Therefore, the thirty-five large-diameter cores designated as TAMU in the Table 4 are being examined for compressional wave and bulk density anisotropy. This is being accomplished by measuring compresssional wave velocities and density at 30 degree intervals

around the circumference of each core and in some cases at 15 degree intervals around half the circumference.

Figures 1 and 2 displays the compressional wave velocity across the diameter of Core KW-SJ-CG-170 measured at 15 degree intervals. One of the most valuable outcome of these type measurements was the fact that the logger was recording, in some instances, the second cycle of the transmitted wave which results in an erroneous drop in velocity of approximately 50 m/sec. This large drop in velocity is attributed to the nature of the liner. It has not been seen in the smaller diameter polycarbonate liners we have used. Figure 3 is a "Velocitygram" of the multilogged Core 170. This figure displays graphically the velocity of the core measured from 2640 measurements across the core diameter. Figure 4 is the resulting "Densitygram" from 2640 density measurements. Figure 2 displays the velocity and density measurements of core KW-SJ-CG-177 at one orientation and Figures 5 and 6 illustrate the "Velocitygram" and "Densitygram" of the core resulting from 3120 measurements. Figure 7 illustrates the density anisotropy of Core 169. Values of anisotropy above 3% are judged to be significant. The resulting velocity and density data will be examined for significant anisotropy, and areas within the core expressing such will be examined to determine the nature of the sediments in terms of size, composition, texture and, fabric which includes particle shape and orientation.

Compressional wave velocity of select cores are being examined in a vertical orientation at a number of locations within the core and in reversed directions. Thus we will be examining vertical and horizontal velocity and density and their anisotropy.

The relationship of density and compressional wave velocity in the Key West cores is very interesting. The density of a sediment is inversely related to it's velocity. Figures 8illustrates various relationships between these two parameters for a number of Key West cores. In Core 283 the velocity of the top of the core is similar to the bottom half while the density at the top half is 9% less than the bottom half. Core 186 illustrates that as density increases velocity also increases. Cores 296 and 173 display almost random results while Cores 176 and 289 show the large separation of the density/velocity relationship between the top half and the bottom half of a core. These cores illustrates the fact that even within two meters of sediment the velocity dependence changes from density to the shear modulas.

Future Analysis

All TAMU cores after being multilogged will be slabbed and stereo-X-rayed in addition to detailed fall cone and vane shear strength measurements made at 2 cm intervals down the full length of the core. Permeability will be measured on the samples used for vertical velocity measurements. We will use X-ray diffraction to determine the down-core ratios of aragonite to calcite in these nearly pure carbonate sediments as we anticipate that variations this parameter will influence sediment bulk density. We have and will continue to collaborate with D. Lambert of NRL and S. Schlock of FAU to relate the measured variations in sediment geologic and geoacoustic properties with variations in the high-resolution seismic profile data. There are several aims: to understand the physical significance of both individual reflectors and the general character of reflectors on high-resolution seismic profiles, to groundtruth and refine estimates of

geoacoustic properties derived from the acoustic data, and to interpret the seismic data in terms of the history of regional environmental processes since the last glacial lowstand of sea level.

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Richardson MD, Bryant WR (1996) Benthic Boundary Layer Processes in Coastal Environments: An Introduction. Geo-Marine Letters, in press.

Orsi TH, Werner F, Milkert D, Anderson AL, Bryant WR (1996) Environmental overview of Eckernförde Bay, Northern Germany. Geo-Marine Letters, in press.

Slowey, N. C. and W. R. Bryant, 1995, Effects of gas and core handling on measurements of compressional wave velocity in ODP Site 893 cores, Scientific Results of the Ocean Drilling Program, v. 146 (Pt. 2), p. 193-197.

Davis, K., N. Slowey, I. Stender, H. Fiedler, W. Bryant, and G. Fechner, in press, Acoustic backscatter and sediment textural properties of inner shelf sands, northeastern Gulf of Mexico, Geo-Marine Letters, in press.

Slowey, N. C., W. R. Bryant, and D. N. Lambert, in press, Comparison of high-resolution seismic profiles and the geoacoustic properties of Eckernförder Bay sediments, Geo-Marine Letters, in press.

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Davis, K. S., W. R. Bryant, N. C. Slowey, and D. N. Lambert, 1994, Reflections on the geoacoustic and geotechnical characteristics in Eckernförde Bay sediments, Proceedings of the Gassy Mud Workshop held at the Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik (FWG), Kiel, 11-12 July, 1994, FWG Report 14, p. 47-53.

Slowey, N. C., W. R. Bryant, and D. N. Lambert, 1995, Geoacoustic properties of Eckernförde Bay sediments and the origin of reflectors on high-resolution seismic profiles, Proceedings of the Modeling Methane-Rich Sediments of Eckernförde Bay Workshop held at the Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik (FWG), Kiel, 26-30 June 1995, FWG Report 22, p. 73-74.

Bryant, W. R., N. C. Slowey, T. H. Orsi, and K. S. Davis, 1995, Processes of macroscale volume inhomogeneity in the benthic boundary layer, Eckernförde Bay, western Baltic Sea, Proceedings of the Modeling Methane-Rich Sediments of Eckernförde Bay Workshop held at the Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik (FWG), Kiel, 26-30 June 1995, FWG Report 22, p. 217-224.

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Slowey, N. C., W. R. Bryant, and D. N. Lambert, 1994, The geoacoustic and geotechnical properties of Eckernförde Bay, Third International Conference on Gas in Marine Sediments, Texel the Netherlands, September 25-28.

Lambert, D. N., D. J. Walter, W. R. Bryant, N. C. Slowey, J. C. Cranford, 1994, Acoustic prediction of sediment impedance, Acoustical Society of America Annual Meeting, Austin Texas, November 28. J. Acoust. soc. Am.,95(5)33222

Bryant, W. R., N. C. Slowey, and D. N. Lambert, 1995, Geotechnical and geoacoustic stratigraphy of the Dry Tortugas, Society for Sedimentary Geology, 1st SEPM Congress on Sedimentary Geology, 13-16 August 1995, St. Petersburg, Florida, 1995.

Orsi, T.H., A.L. Anderson, W.R. Bryant, K. Davis, R. Rezak and N. Slowey. 1995, Computer tomography of macroscale heterogeneity of carbonate muds, Marquesas Keys and Dry Tortugas, South Florida, Society for Sedimentary Geology, 1st SEPM Congress on Sedimentary Geology, 13-16 August 1995, St. Petersburg, Florida, 1995

EVENTS

William R. Bryant was Co-Guest Editor for two special issues of the *Journal of Geo-Marine Letters* (1996), which deals with the research results of NRL Coastal Benthic Boundary Layer Program in Eckernförde Bay, Germany.

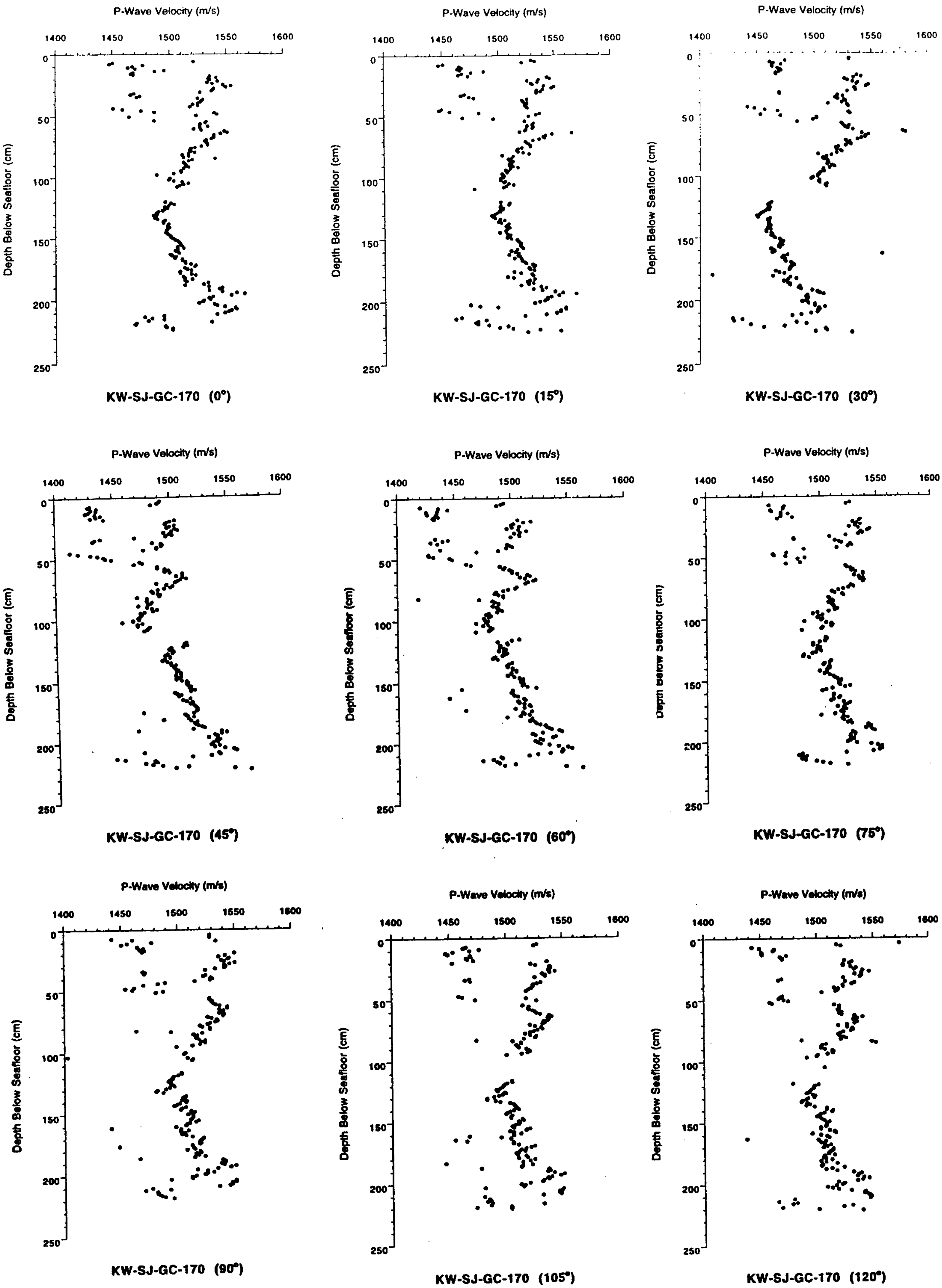


Figure 1. Compressional wave velocity of Core KW-SJ-CG-170 measured at 15 degree intervals.

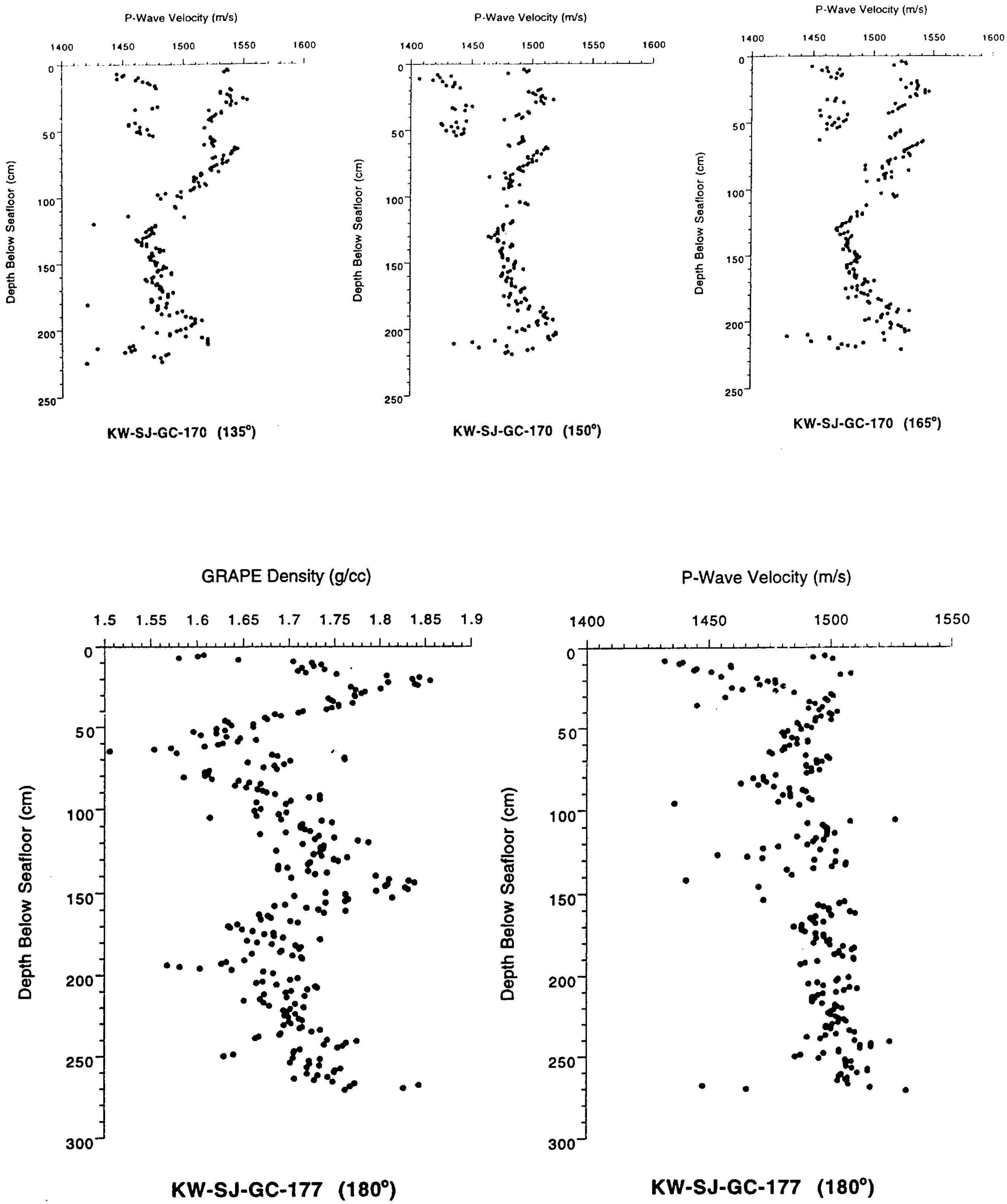


Figure 2. Compressional wave velocity of Core KW-SJ-CG-170 measured at 15 degree intervals and the density and velocity of Core KW-SJ-CG-177 measured at one orientation.

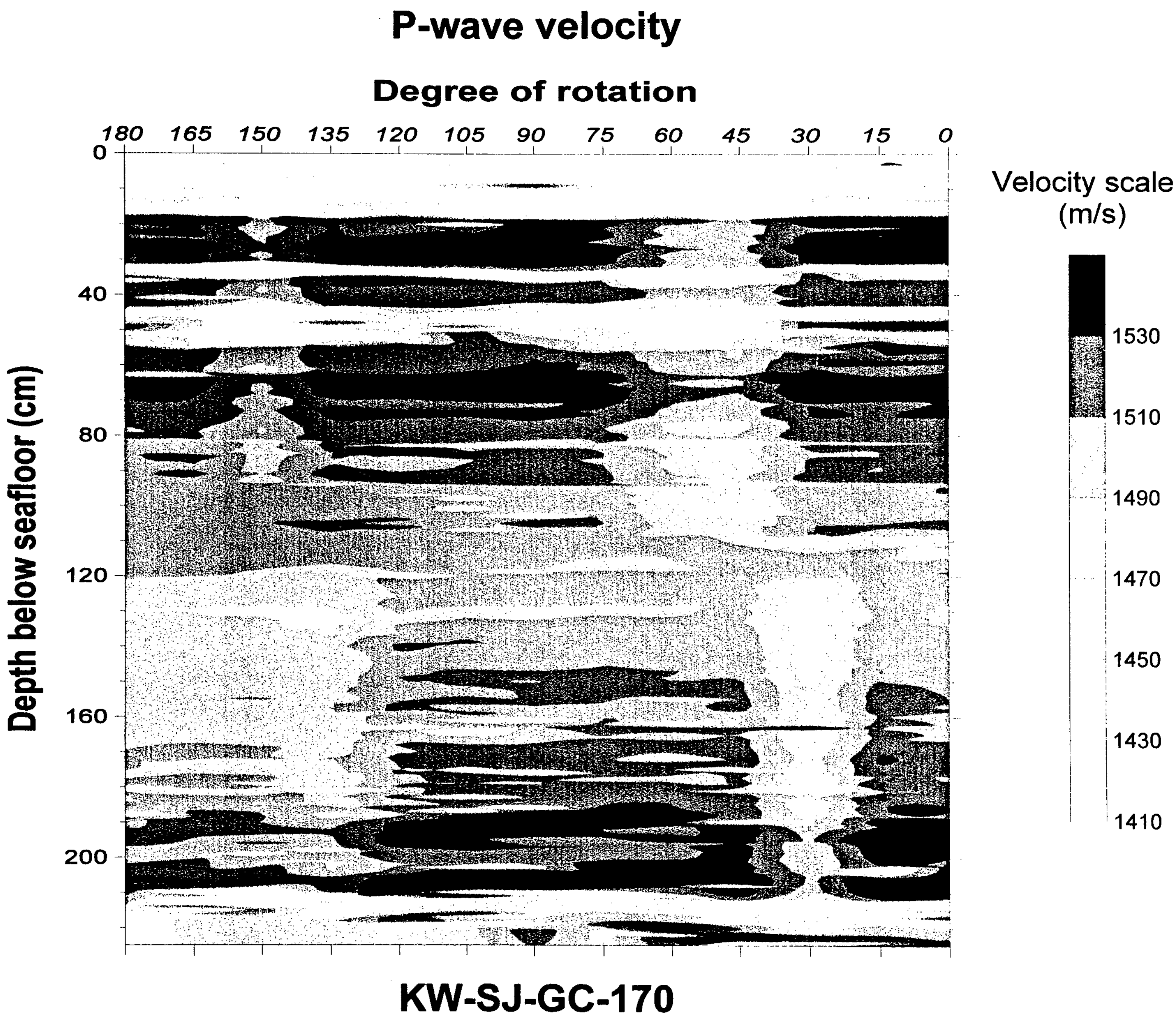


Figure 3. Velocitygram of Core KW-SJ-CG-170

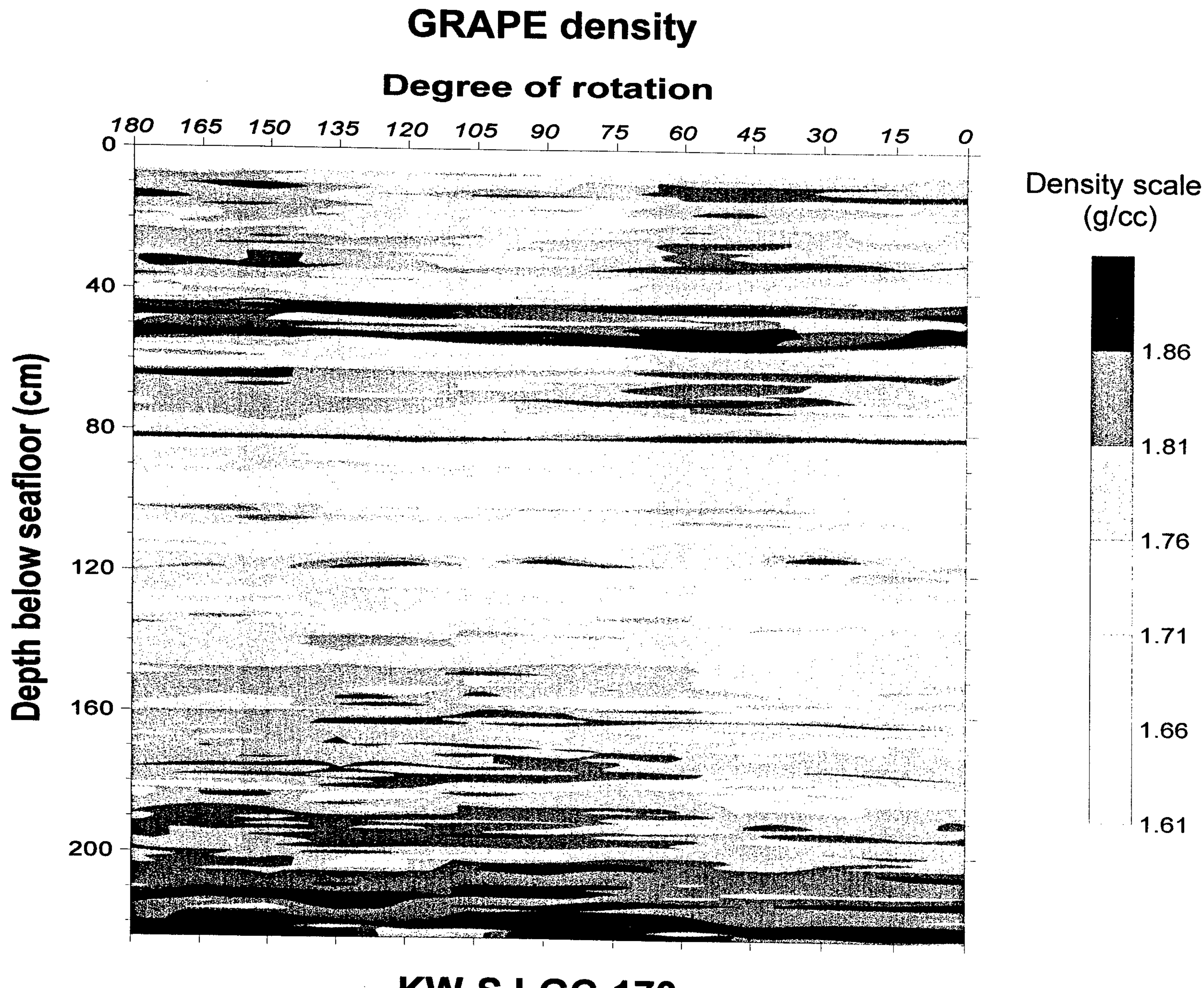


Figure 4. Densitygram of Core KW-SJ-CG-170

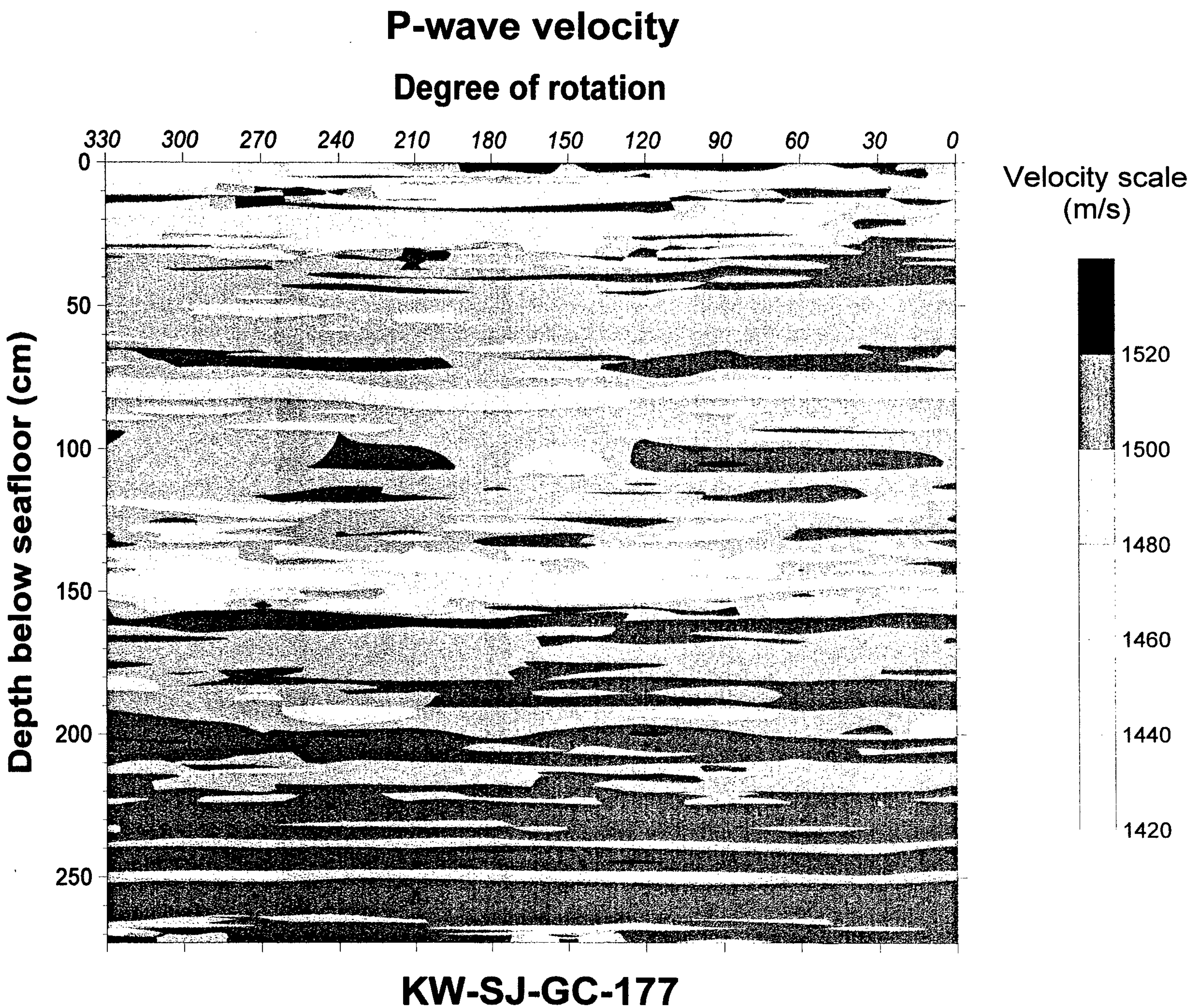


Figure 5. Velocitygram of Core KW-SJ-CG-177

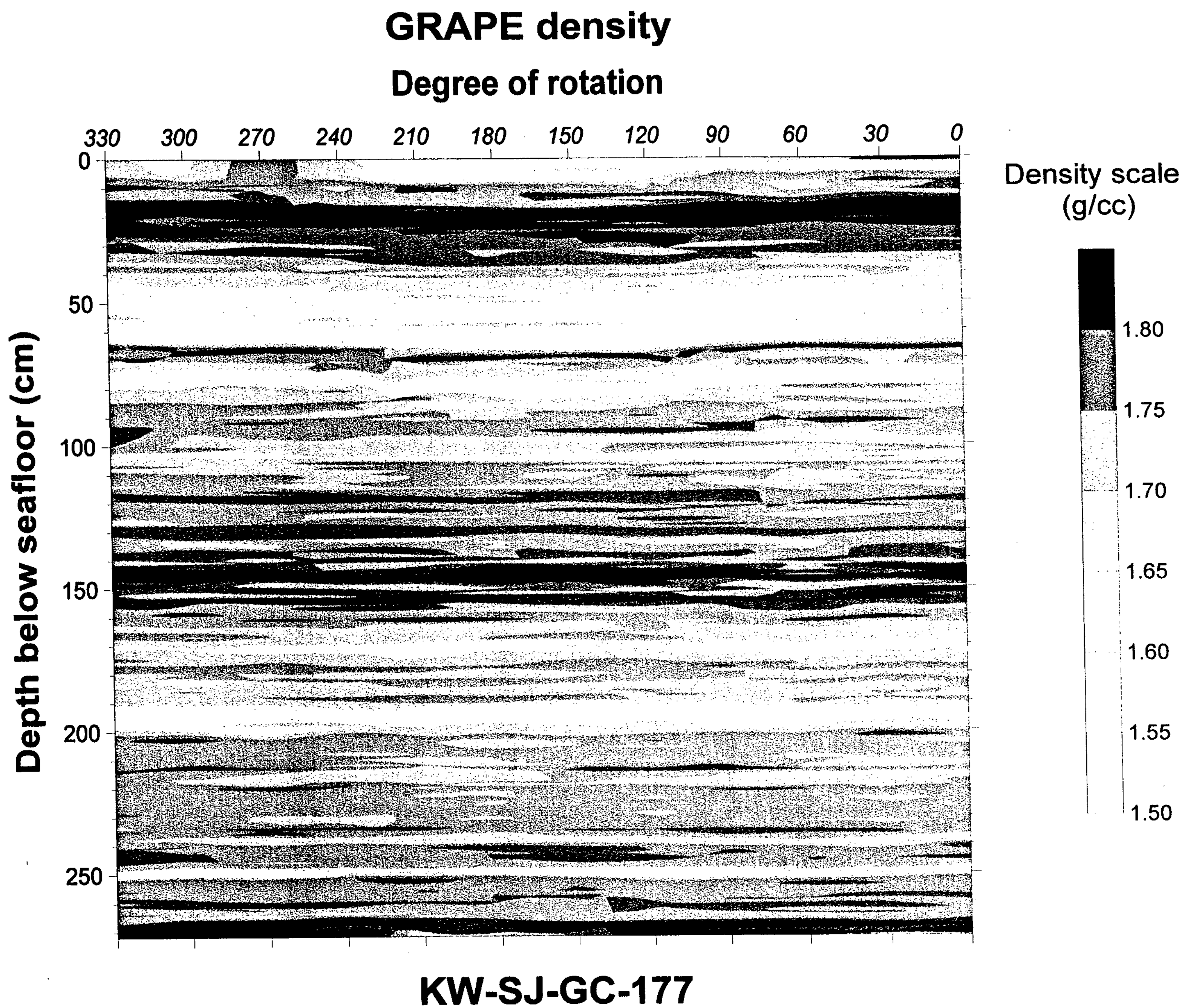


Figure 6. Densitygram of Core KW-SJ-CG-177

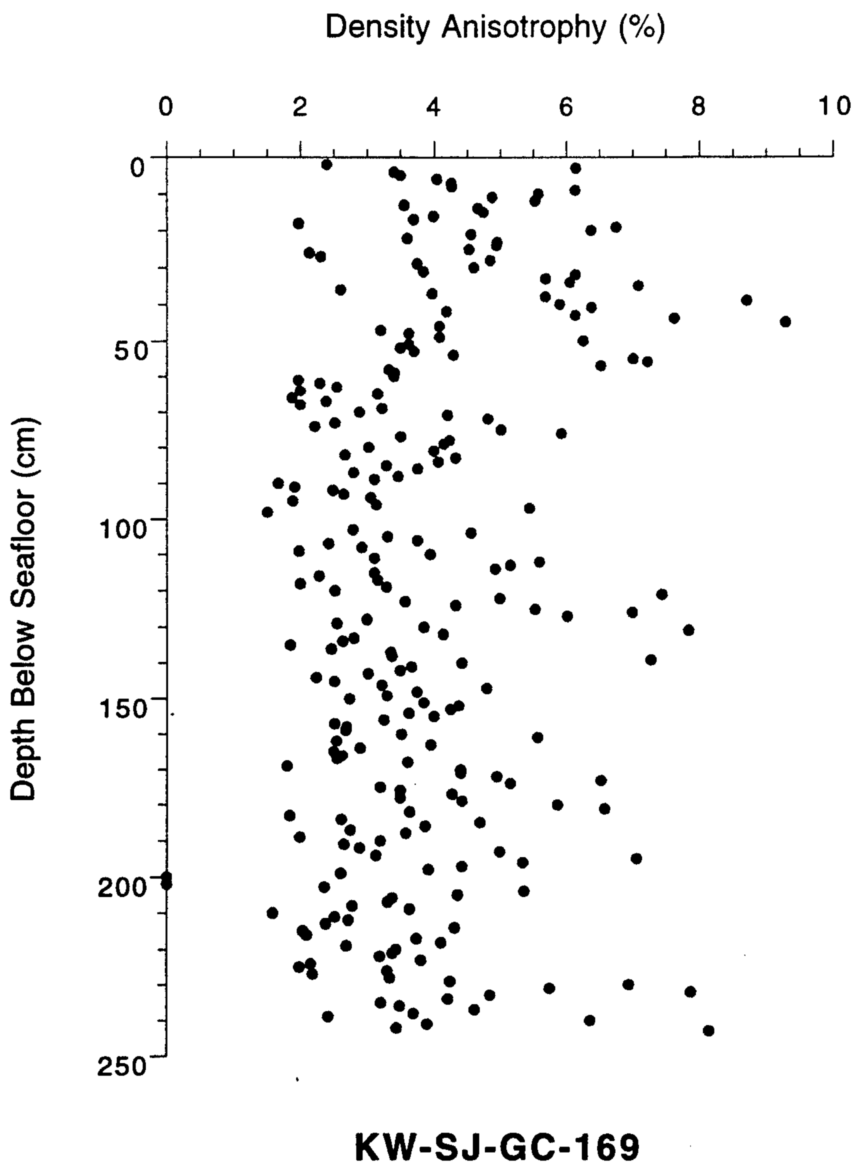


Figure 7. Density anisotropy of Core KW-SJ-CG-169.

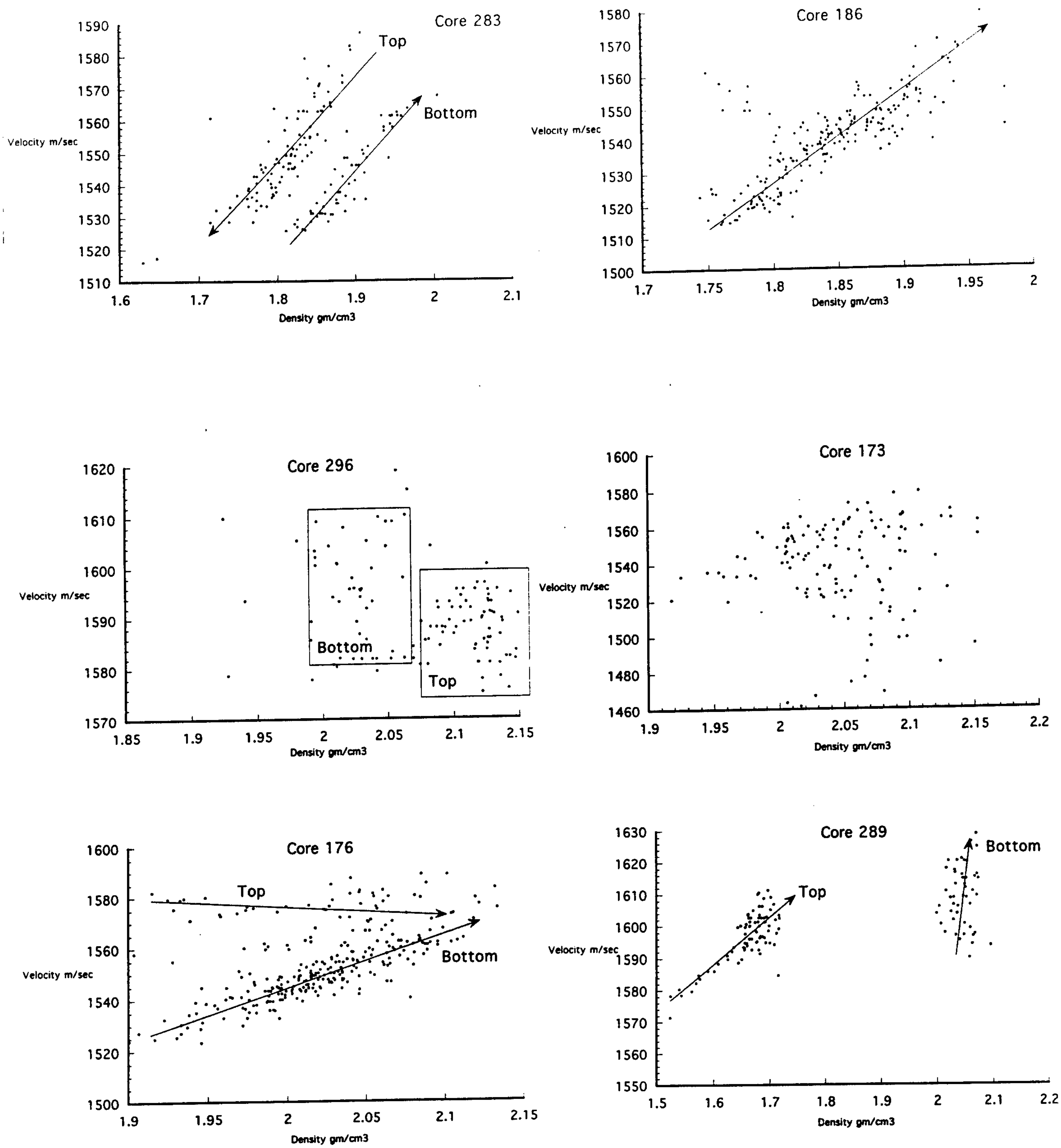


Figure 8. Various relationships between sediment density and compressional wave velocity.

2.6 Bottom Backscatter Measurements of Key West, Florida (Principal Investigators: N.P. Chotiros and R. Altenberg)

R. A. Altenburg and N.P.Chotiros
Applied Research Laboratories
University of Texas at Austin

I. Introduction

The CBBL Key West 95 campaign provided an opportunity to measure backscattering strength for a carbonate bottom and correlate those measurements with a wide range of geophysical bottom types. A 200 kHz sonar mounted on a remotely operated vehicle (ROV) with a television camera was used to make the measurements

The ROV mounted sonar was proven to be useful for making bottom backscatter measurements. It can be quickly deployed and retrieved by a small crew while the support ship is anchored in a simple mooring. Unlike a towed system, a small, well surveyed area can be measured but without the logistical problems of a bottom mounted system. In addition, video surveys of the test site provided by the television proved to be valuable in interpreting the backscatter measurement results.

II. Accomplishments

Hardware

An existing sonar, mounted on a ROV and was modified for this project. Principal modifications included fabricating an interface to the sonar data line. This interface made possible the conversion of the analog sonar data to digital format for off-line storage. The conversion process was controlled by a Macintosh computer running a National Instruments LabVIEW program. The digital data was reviewed for quality at sea and analyzed at a latter time.

Seatest

All measurements were made in the Dry Tortugas test range during the February 1995 Key West CBBL/SRP campaign. The site map shows the location of the 9 test sites. Also indicated on the map is the mean grain size of the sediment determined from grab or core samples taken during the cruise. The experimental sites are grouped into four general bottom types: soft, medium, hard, and reef.

Results

Results of the measurements are shown on the figures below. During the backscattering measurements, the sonar was maintained at a constant height above bottom while a set of

multiple pings of data were recorded. Each set appears as separate lines plotted on the graphs Also included on the figures are single video frames captured from the VCR recording. They are representative of the video survey at the measurement site.

The results are summarized in the graph which shows a plot of backscattering strength as a function of normalized grain diameter at a 10 deg grazing angle. Nolle's results appear to provide a lower bound for the data. His measurements were carefully controlled laboratory experiments. The sediments for his measurements were degassed, had a smooth interface, and were of a uniform grain size. Backscattering strength measurements, taken from the literature, are plotted on the graph in black; measurements resulting from the current experiments are plotted in red. The Key West measurements are consistent with the other findings, which find that the backscatter strength is higher then Nolle's values.

Surface roughness may contribute to the higher values, but, as indicated by the TV pictures, the bottom was reasonably smooth (accept at the reef site). The nonuniform sediment grain size distribution is also a factor.

Frank Boyle has shown that gas fractions, in the form of bubbles in sediment, as small as 10^{-6} can produce a 20 dB increase in backscatter strengths if the bubbles are near resonance with the sound field. A diver used a funnel with a test tube placed over the small opening and a rod attached to the other side to capture gas samples. This was done by stirring the bottom with the rod and collecting any rising gas bubbles with the large end of the funnel. A small gas bubble was collected and can be seen in the picture. Although not a quantitative measurement, this experiment does demonstrate that gas was indeed present in the sediment. The biological activity in the benthic layer provides a probably source for the entrapped gas.

III. Preliminary Conclusions

- A remotely operated vehicle with TV camera and sonar was successfully deployed at sea during the Key West 95 campaign

- Bottom backscattering strength measurements were measured at 8 sites in the test area and results correlated with geophysical data

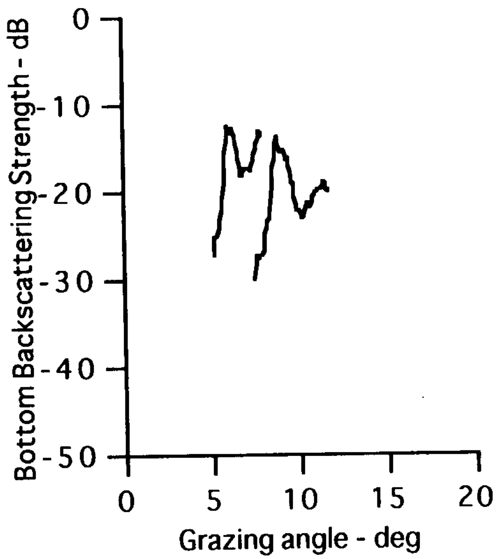
- Backscattering strength values as a function of dimensionless grain size are consistent with existing data base

- It is likely that minute amounts of gas bubbles affected the backscattering strength

IV. Publications

Measurements of the acoustic (200 kHz) backscatter from a carbonate sediment at low grazing angles. Robert A. Altenburg and Nicholas P. Chotiros, 130th Meeting of the Acoustical Society of America, 1995.

Site 1



Hard bottom

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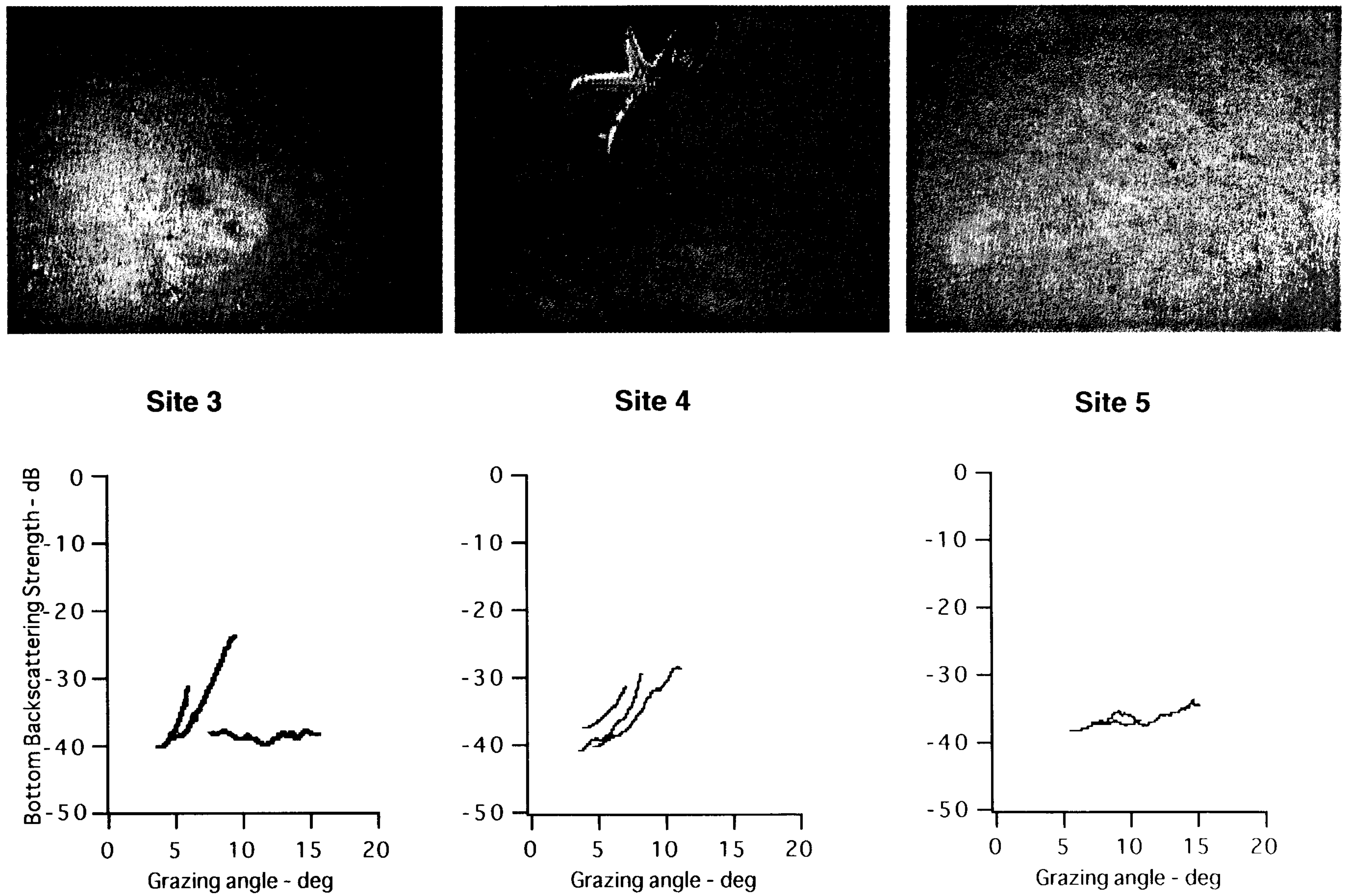

Medium bottom

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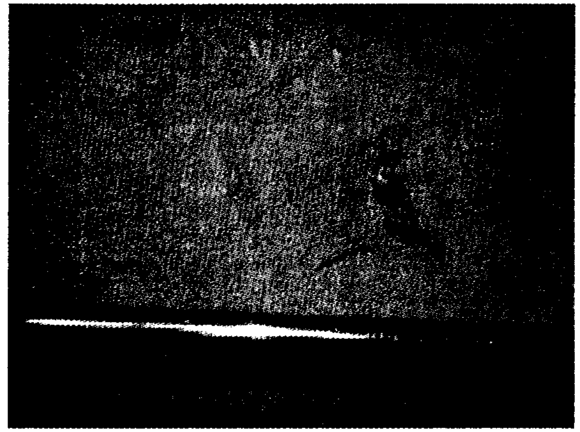
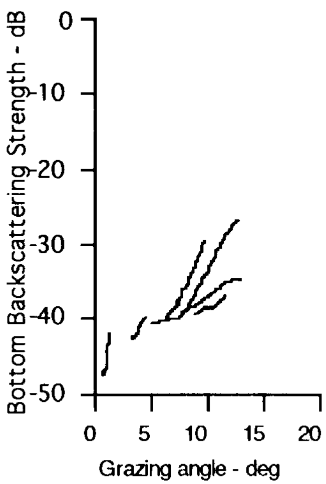
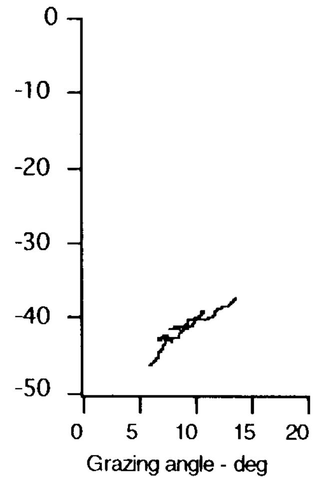


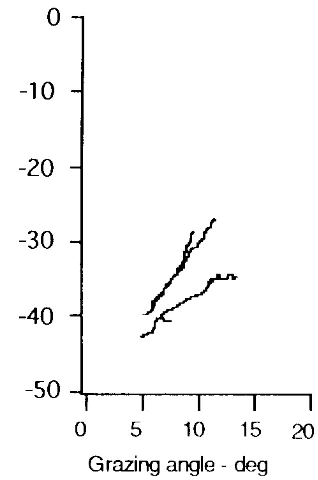
Site 6



Site 7



Site 8



Soft bottom

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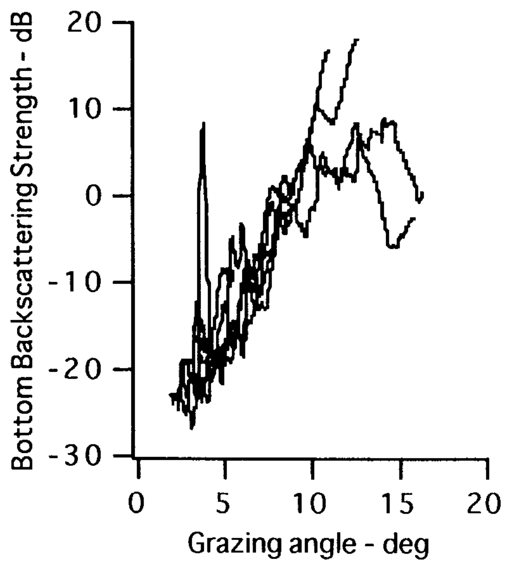
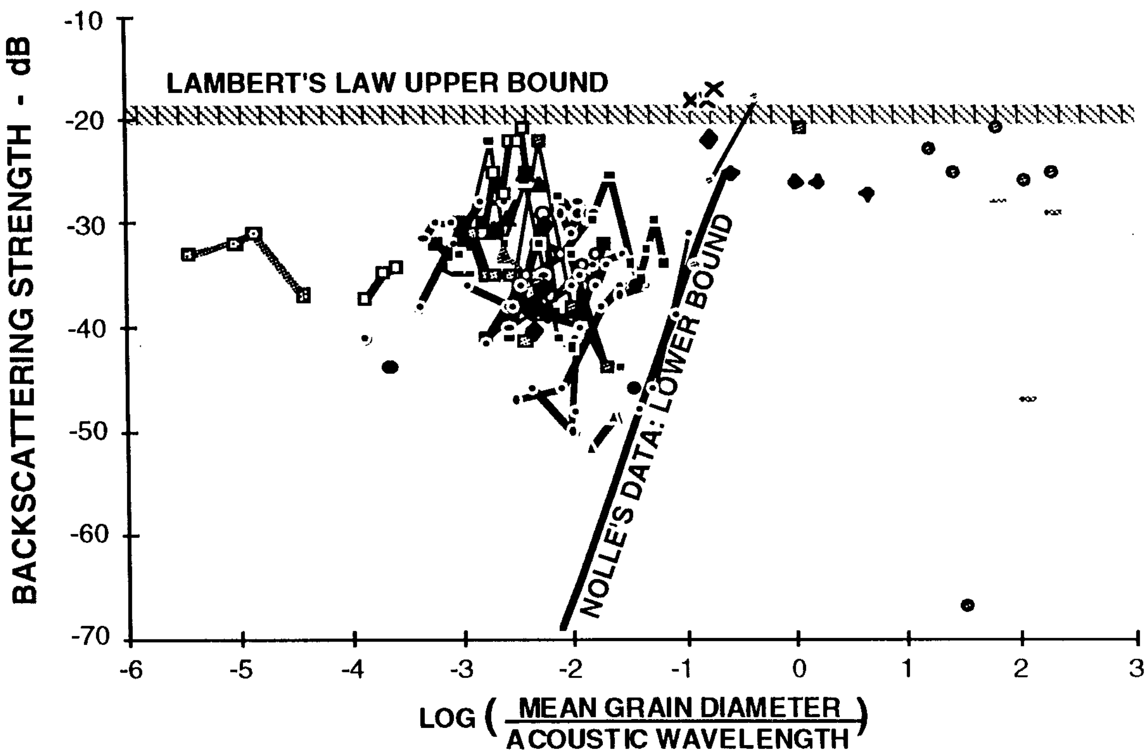
Site 9



Reef



BOTTOM BACKSCATTERING STRENGTH
AS A FUNCTION OF MEAN GRAN SIZE
1 kHz to 1 MHz
AT A GRAZING ANGLE OF 10°

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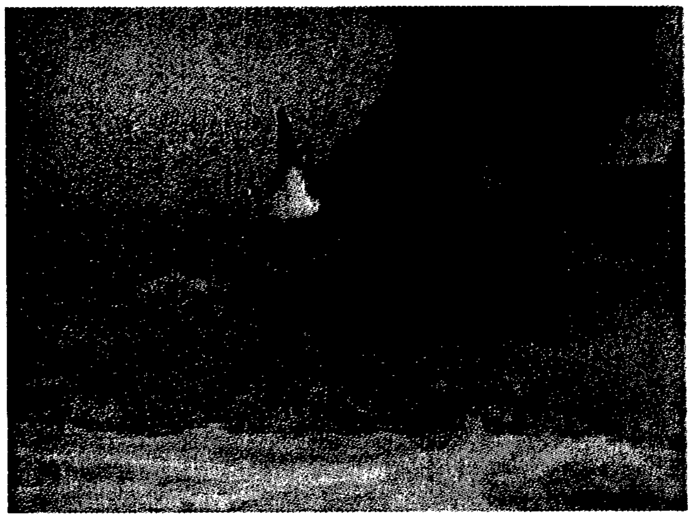
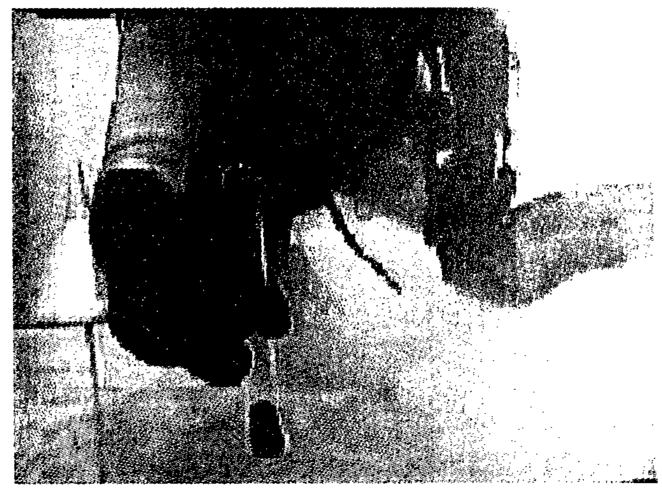




GAS CAPTURE

2.7 Geophysical Approaches to Determining the Geotechnical Characteristics of Sea Floor Sediments (Principal Investigators: A. Davis, D. Huws, R. Haynes and Jim Bennell)

Angela Davis, Dei Huws, Ron Haynes and Jim Bennell
School of Ocean Sciences
University of Wales, Bangor
Menai Bridge LL59 5EY, UK

INTRODUCTION

The main objective of the project was to collect geophysical data to assist the physical characterisation of the carbonate sediments at the CBBL Key West sites. These data were to be collected using underway techniques which were successfully proven during the 1994 experiments at the CBBL site in Eckernförde Bay, Germany.

KEY WEST EXPERIMENTS

UWB's experiments involved measurements with the bottom-towed geophysical sled device `Magic Carpet' to obtain information on sediment shear wave and electrical property variability, and surveying with a digital multi-channel high resolution sub-bottom profiler, the ultimate objective of the latter experiments being the extraction of geotechnically-significant seismic attributes from the reflection response.

Shear wave, electrical resistivity and sub-bottom reflection measurements were made at two of the three CBBL test sites in the Florida Keys: Dry Tortugas and Rebecca Shoals, with an additional independent sub-bottom profiler survey carried out at the third site i.e. at the Marquesas Keys.

SHEAR WAVE MEASUREMENTS

Travel-time data recorded with the magic carpet were inverted to provide information on the spatial variability of shear wave velocity in the upper 2-3 metres of the sediment cover. A total of 435 independent shear wave velocity measurements were made in the Dry Tortugas and Rebecca Shoals. In most instances the shear wave measurements were accompanied by measurements of the electrical formation factor (to investigate sediment pore space properties).

Dry Tortugas

The magic carpet system was bottom-towed for a total of 9.5 hours along 6 tracks near the Dry Tortugas. Higher than expected shear wave velocities (40-80 m/s in the upper 0.5 metres) were recorded from the soft carbonate sediments in the vicinity of the CBBL Program experimental tower sites (lines 26 and 27; see accompanying figures), and most records indicated a marked

increase in velocity with depth within the upper two metres of the sediment column. This would imply a significant increase in sediment stiffness with depth.

Rebecca Shoals

One line (1.5 hours survey time) was run with the magic carpet in the Rebecca Shoals area to help characterise the physical properties of the more sandy carbonate materials. As expected, the surface sediment shear wave velocities were much higher than within the carbonate muds (typically 120m/s), though velocity-depth gradients were higher than expected.

A sediment sample was taken along the Rebecca Shoals line to provide the necessary material for future geophysical/geotechnical laboratory testing, with the primary objective to produce control data to aid the in situ interpretation. Laboratory measurements will include resonant column testing to provide additional information on low strain shear and compressional attenuation (to aid seismo-acoustic modelling), and geophysically-instrumented and cyclic triaxial tests to help define the liquefaction susceptibility of the sediment under varying load conditions.

MULTI-CHANNEL SUB-BOTTOM PROFILING

High resolution sub-bottom profiler data were acquired along the lines surveyed with the magic carpet and along additional lines set up within the 3 main CBBL test areas. These were collected using a broad-band impulsive source (a Uniboom), an Elics Delph-24 multi-channel digital acquisition system, and mutli-channel receiver arrays. The acquired data are currently being processed to provide geotechnically-significant seismic attributes (velocity, acoustic impedance etc.), and it is anticipated that the results of this work will be included in a paper to be submitted for consideration for inclusion in the proposed `Key West' special issue of Geo-Marine Letters. The following represents a qualitative view of sub-bottom features based on a preliminary interpretation of the digital sub-bottom profiler data.

Dry Tortugas

In the Dry Tortugas area surveying concentrated on the CBBL test site to the south of the islands. Line 26, one of the magic carpet lines, revealed a small sediment infilled channel at the southern end, overlying the probable Pleistocene (Key Largo Limestone) to a thickness of 2-3 metres. From the nature of the infill and the seismic character (examination of asymmetric amplitude and reflectivity envelope plots computed from the Hilbert transform), this sediment is believed to be fine-grained limey-mud. Approaching the northern end of the basin the bedrock rises steeply until it flattens off to form a near-horizontal platform. A thin (1.5-2 metre) bank of sediment (carbonate sand ?) is observed on this platform between shots 3470-4700.

Marquesas Keys area

Lines shot in the Marquesas Keys area generally found 2-4 metres of Holocene sediment, probably carbonate mud, overlying a rugged probably Pleistocene bedrock surface. The top of the probable Pleistocene unit exhibits a number of irregular reflectors which are tentatively interpreted as sub-aerially formed weathering layers. In places e.g. around shot point 1900 on line 29 (see accompanying figure - asymmetric amplitude plot), a prominent solution feature is observed in the sub-surface topography. Similar features were observed along several of the lines shot in this area helping confirm the hypotheses about the geological evolution of the area. In particular, the large solution (?) feature around shot 1400 on line 31 truncates at least one of the reflectors observed in the Pleistocene indicating that it pre-dates or is contemporaneous with the last episode of sub-aerial exposure. In addition, the material of these weathered layers, or calcretes, is apparently less hard than the weathered bedrock, as the amplitude of the reflectivity envelope is less than that of the bedrock.

The probable weathered layers and calcretes at the top of the Pleistocene show a number of features such as truncations. The resolution of these truncations indicates that the boomer is observing features with a resolution to the order of 10s of cm.

SUMMARY

It is anticipated that completion of the analysis of the combined data set i.e. sub-bottom profiler and bottom-towed sled, will provide useful information on the spatial variability of the sea floor and subsurface sediments, and will assist in the understanding of process/property interactions for this carbonate-rich environment.

PUBLICATIONS

Davis A M and M D Richardson (1995) `Geophysical Remote Sensing of Sea Floor Sediment Properties' Proceedings of European Environmental and Engineering Geophysics Society, Turin, Italy

Richardson M D and A M Davis (1995) `Sea Floor Sensing of Sediment Shear Wave Properties' Proceedings of the European Environmetal and Engineering Geophysics Society, Turin, Italy.

Haynes R and A M Davis (1995) `Using Seismic Reflection Attributes to Resolve Sub-surface Sediment Characteristics' Proceedings of the Workshop `Modelling Methane-Rich Sediments of Eckernfeorde Bay', (ed T F Wever), FWG Report 22, 50-57.

Huws D , A M Davis and J Pyrah (1995) `Using Shear Wave Velocity and Electrical Resistivity to Resolve the Spatial Variability of Sea Floor Sediment Properties in Eckernförde Bay' Proceedings of the Workshop `Modelling Methane-Rich Sediments of Eckernförde Bay', (ed T F Wever), FWG Report 22, 189-193.

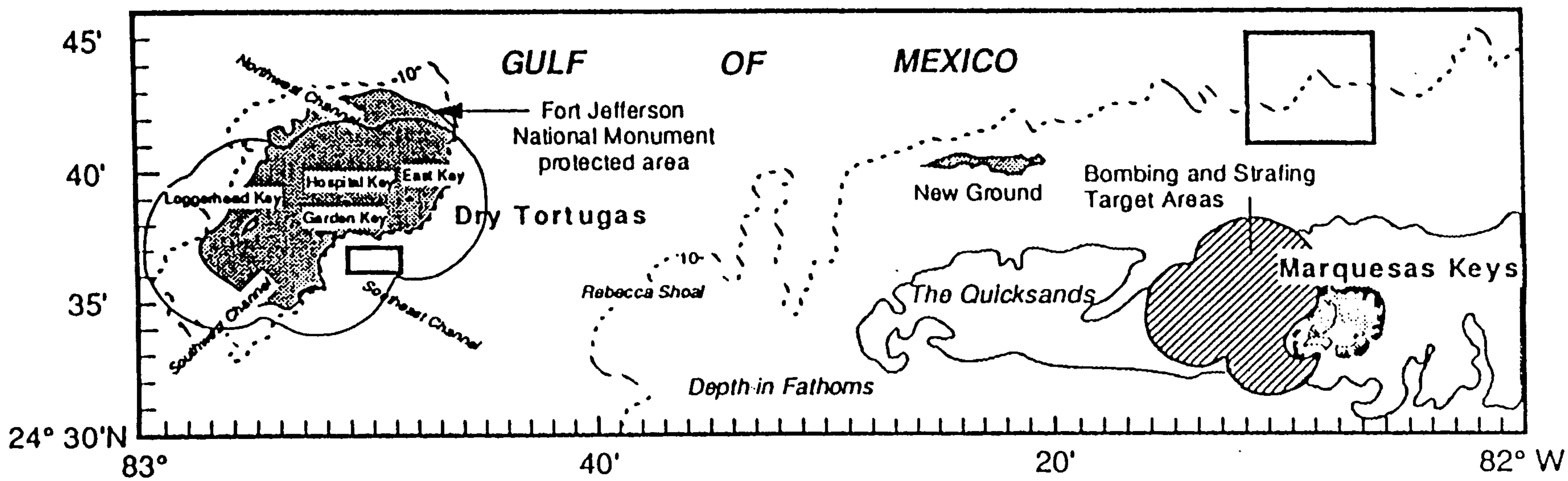
Davis A M, Huws D G, Haynes R and JD Bennell (1995) `Geophysical Sea Floor Sensing in a Carbonate Sediment Regime' SEPM Congress, St Pete Beach, Florida.

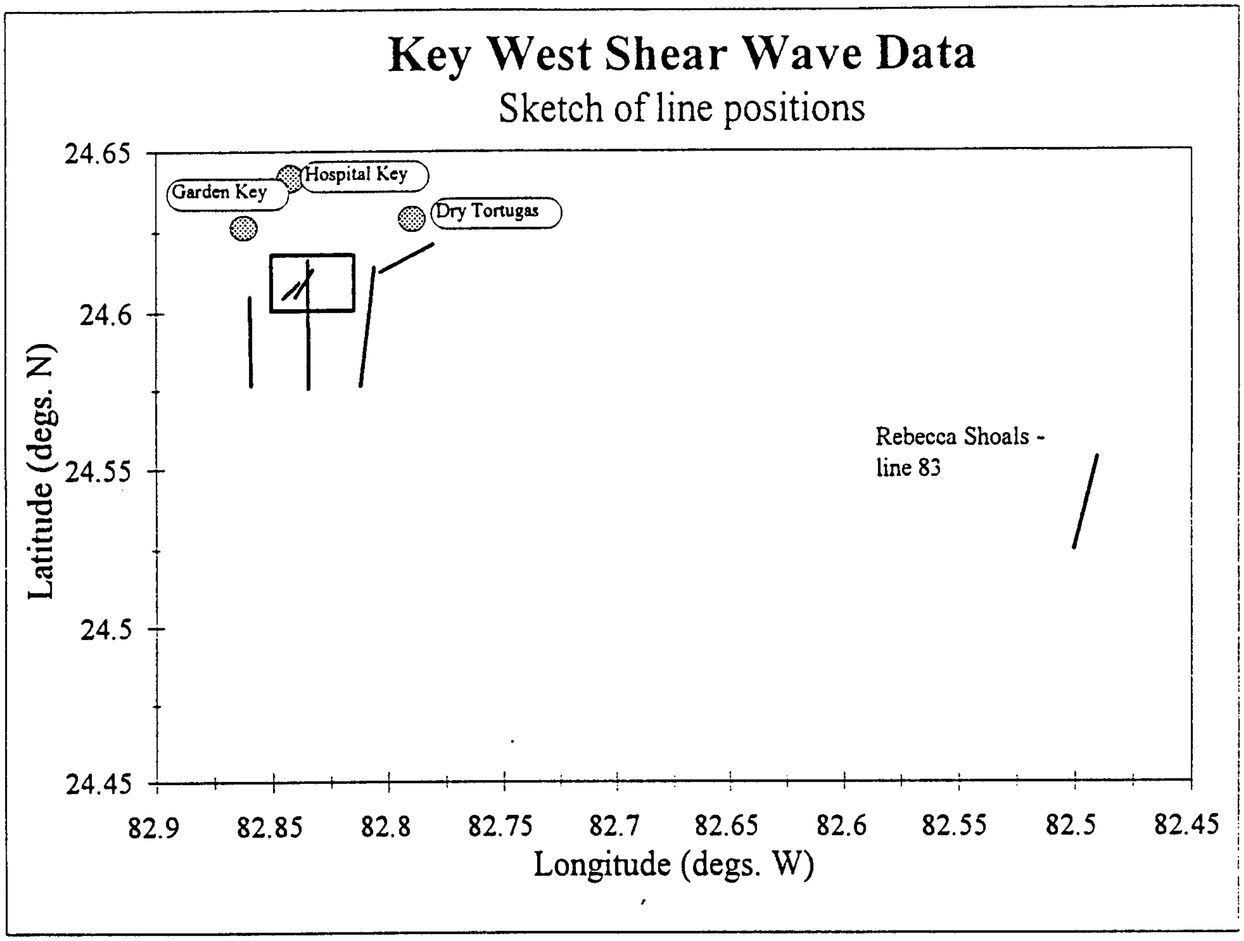
PRESENTATIONS

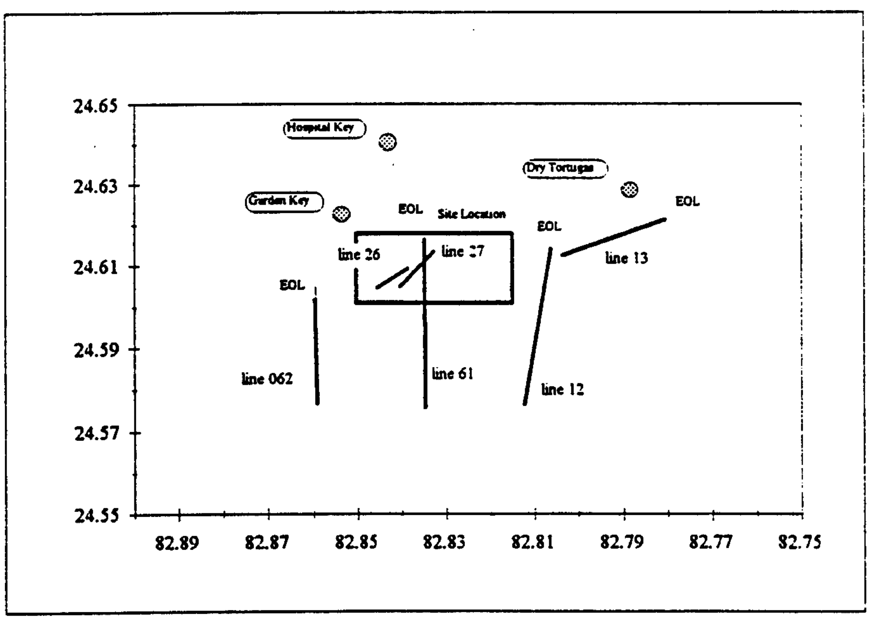
Geophysical experiments in a gassy mud environment: CBBL Special Research Program. Presentation by A M Davis to the ERASMUS Mercator Group, 5th Annual Intensive Course held in Gent, Belgium, Sept.95

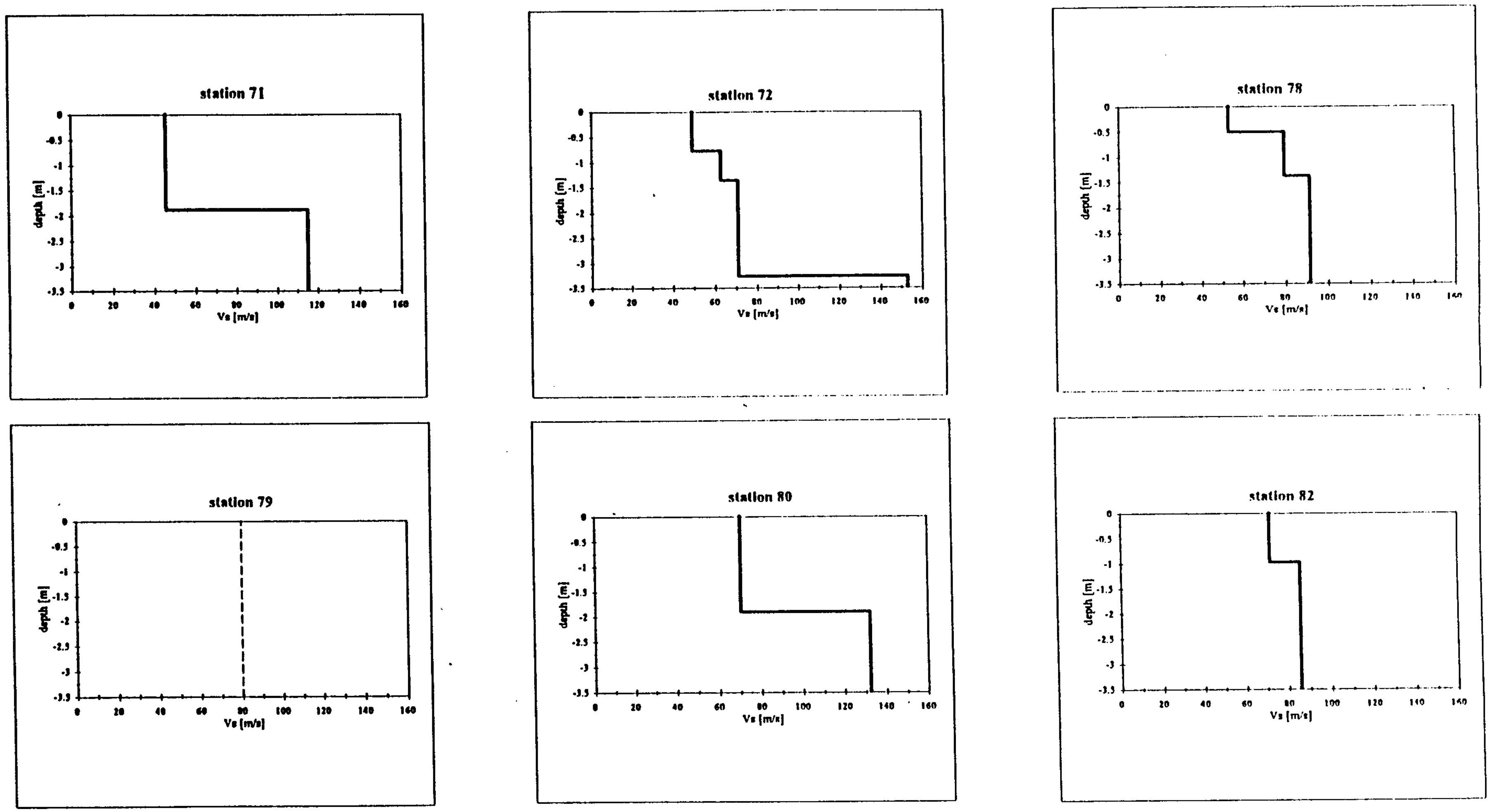
*Papers presented at the European Environmental and Engineering Geophysics Conf., Turin, Sept 95 (Presentations by A M Davis).

**Papers presented at the Eckernförde Workshop `Modelling Methane-Rich Sediments', June 95.
(Presentations by first authors)

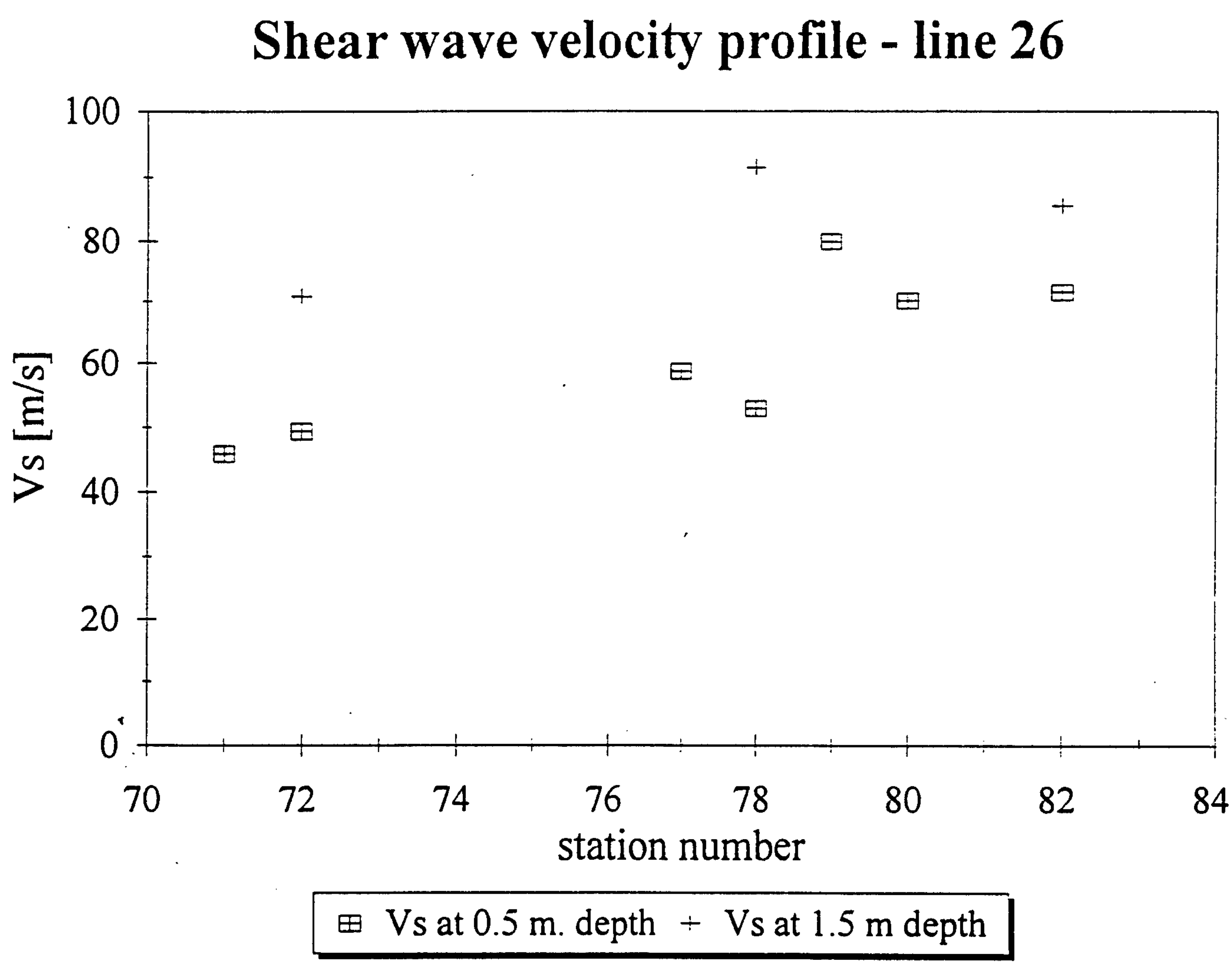

GULF OF MEXICO
Fort Jefferson
National Monument
protected area
Dry Tortugas
Northwest Channel
Southwest Channel
Southeast Channel
Loggerhead Key
Hospital Key
East Key
Garden Key
10
Rebecca Shoal
New Ground
Bombing and Strafing
Target Areas
The Quicksands
Marquesas Keys
Depth in Fathoms
45'
40'
35'
24° 30'N
83°
40'
20'
82° W


Key West Shear Wave Data
Sketch of line positions
24.65
24.6
24.55
24.5
24.45
Latitude (degs. N)
Garden Key
Hospital Key
Dry Tortugas
Rebecca Shoals -
line 83
82.9
82.85
82.8
82.75
82.7
82.65
82.6
82.55
82.5
82.45
Longitude (degs. W)

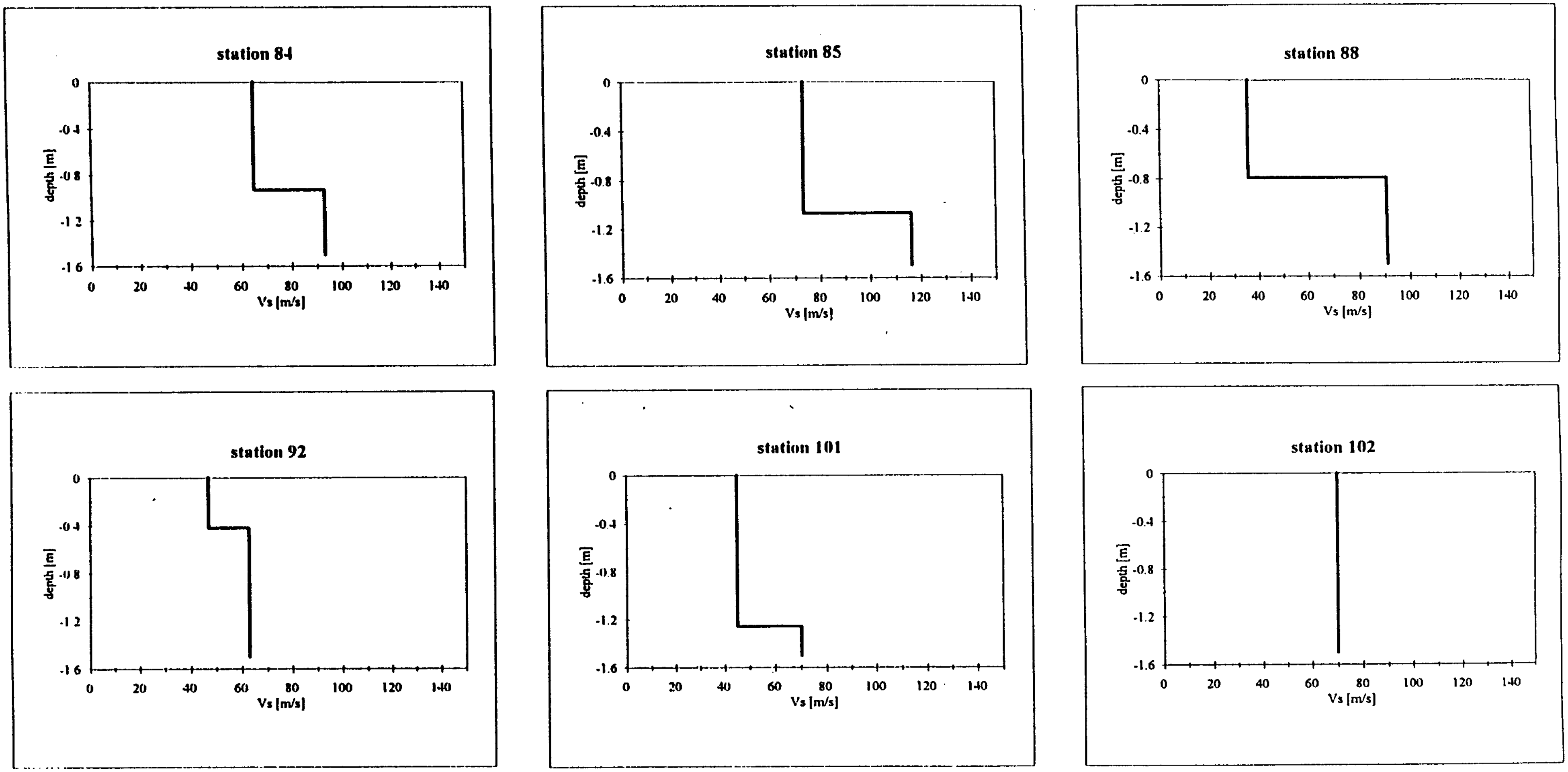

24.65
24.63
24.61
24.59
24.57
24.55
Hospital Key
Dry Tortugas
Garden Key
EOL
Site Location
EOL
EOL
line 26
line 27
line 13
EOL
line 062
line 61
line 12
82.89
82.87
82.85
82.83
82.81
82.79
82.77
82.75



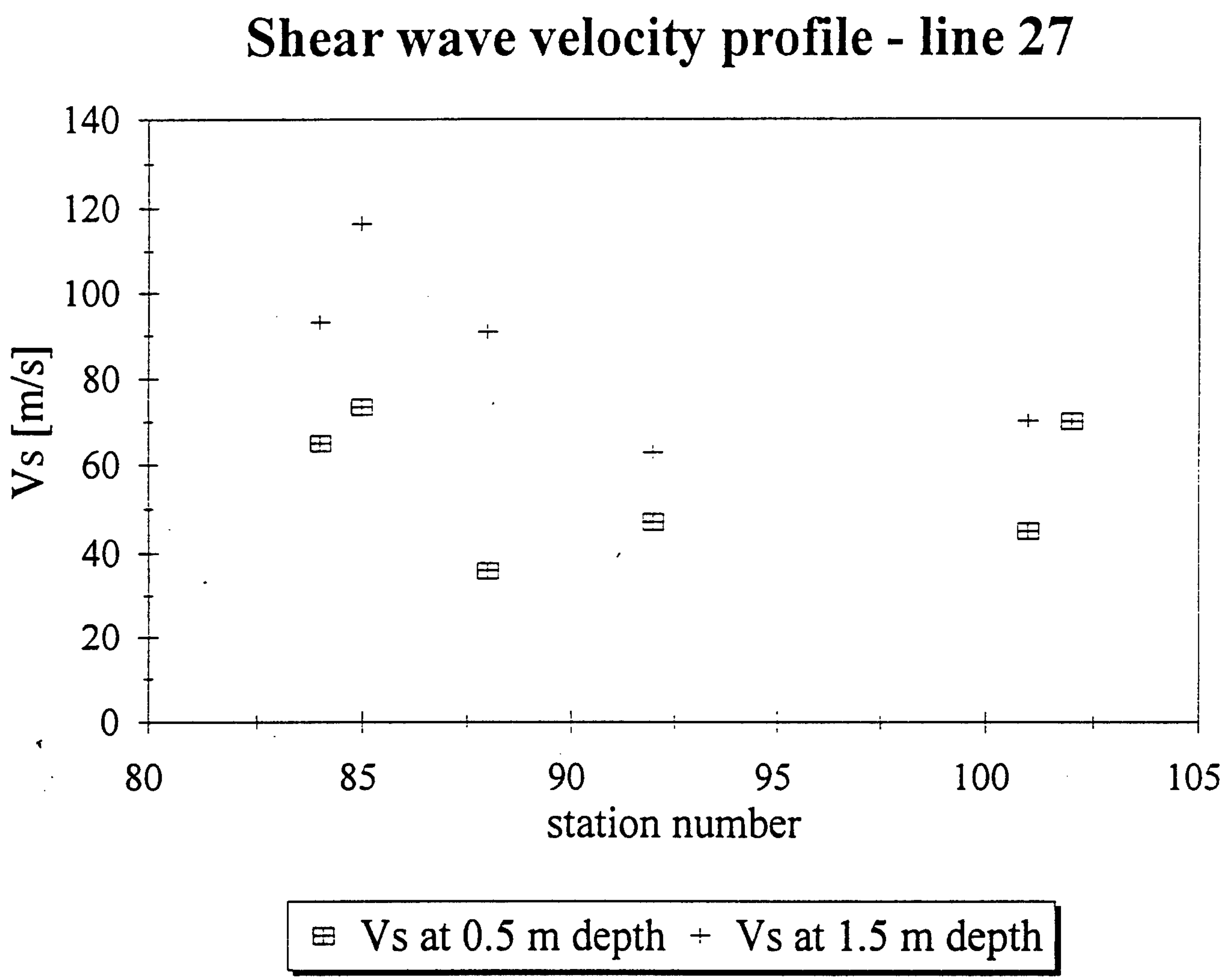
Shear wave velocity-depth profiles along line 26 (in vicinity of APL tower site)

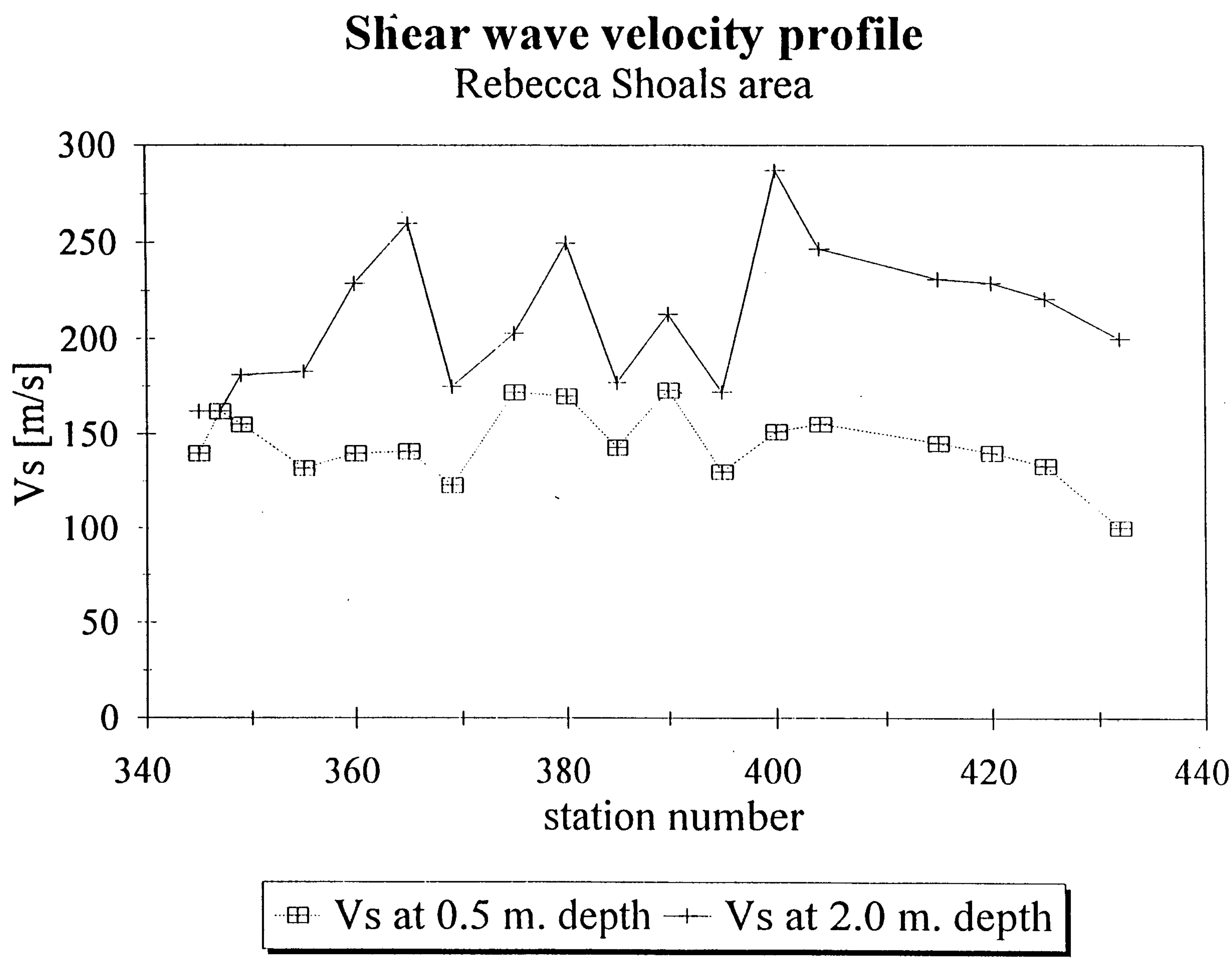


Shear wave velocity profile - line 26
100
80
60
40
20
0
Vs [m/s]
70
72
74
76
78
80
82
84
station number
Vs at 0.5 m. depth
Vs at 1.5 m depth



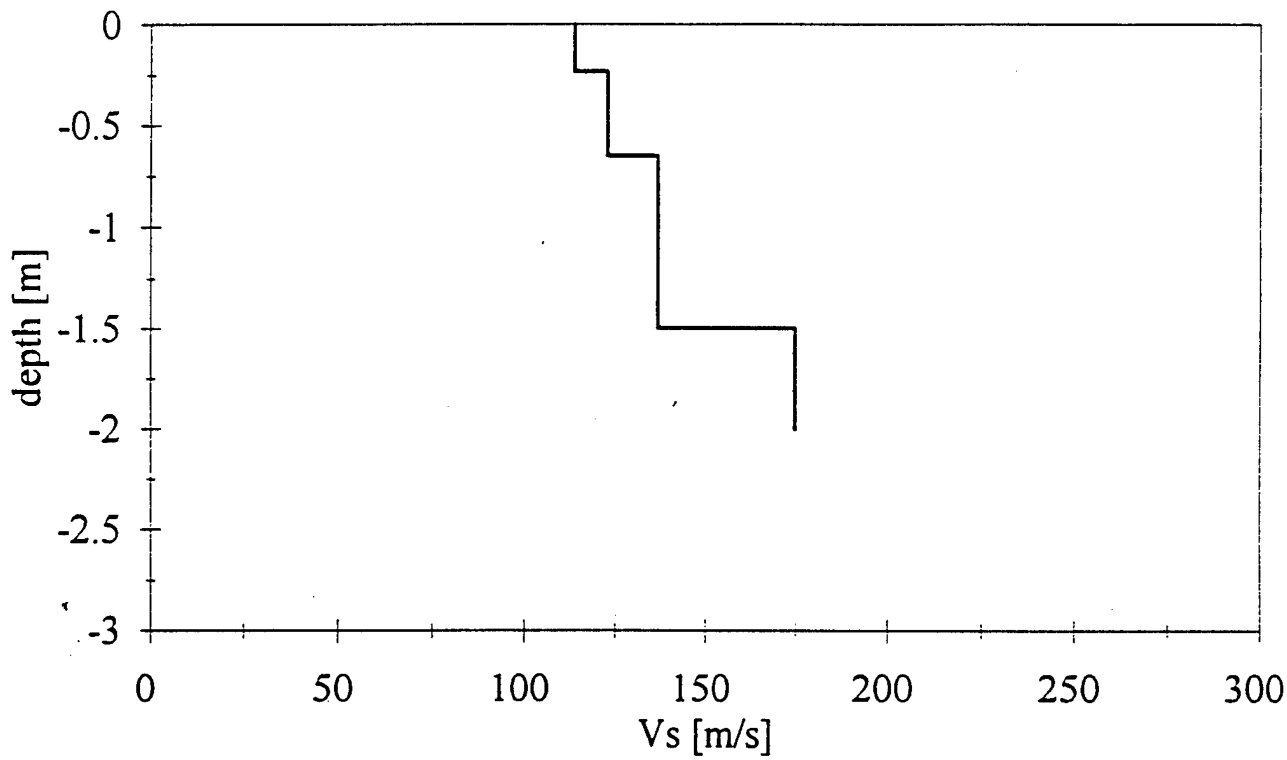
Shear wave velocity-depth profiles aling line 27 (in vicinity of APL tower site)

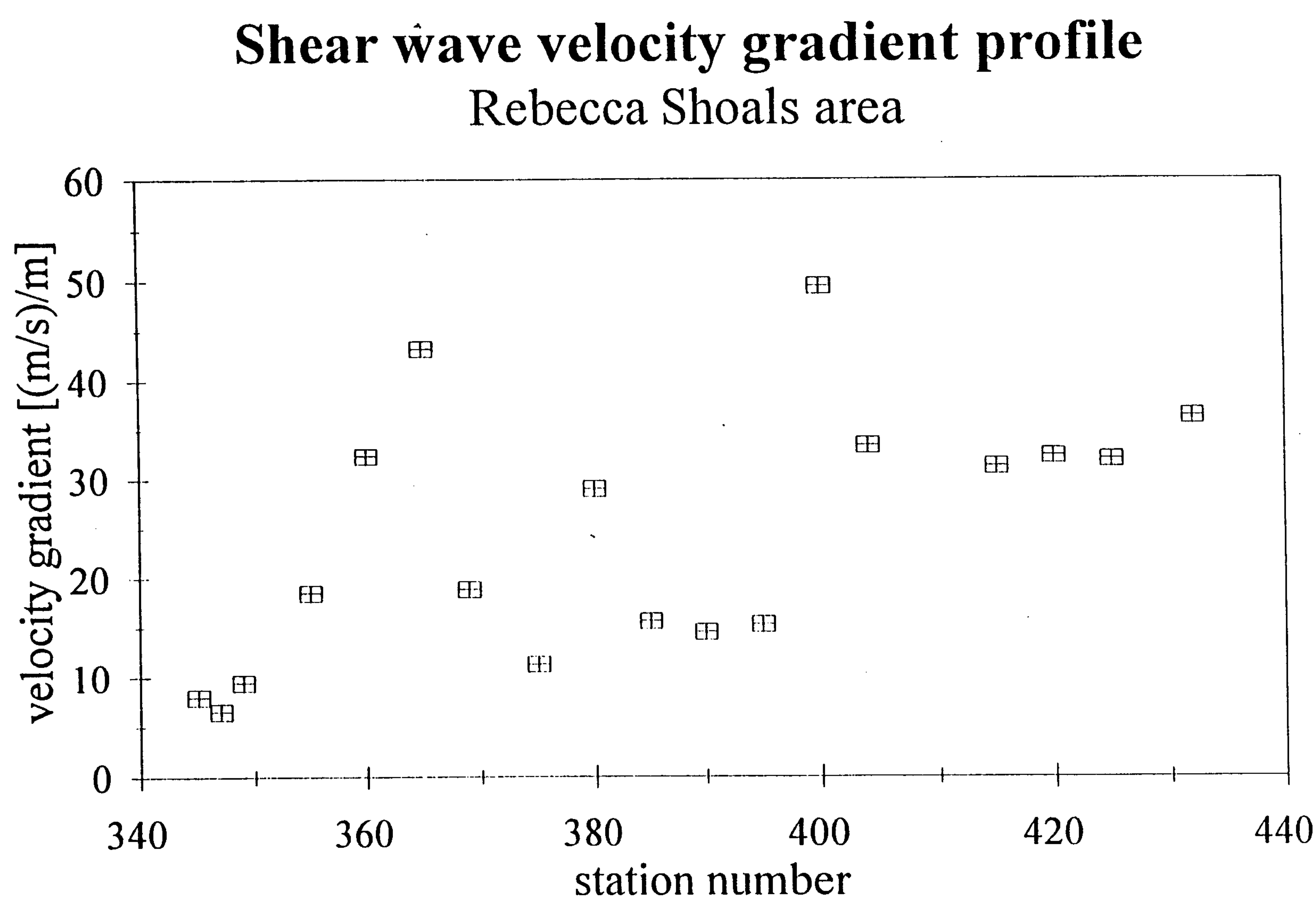

Shear wave velocity profile - line 27
140
120
100
80
60
40
20
0
Vs [m/s]
80
85
90
95
100
105
station number
Vs at 0.5 m depth
Vs at 1.5 m depth

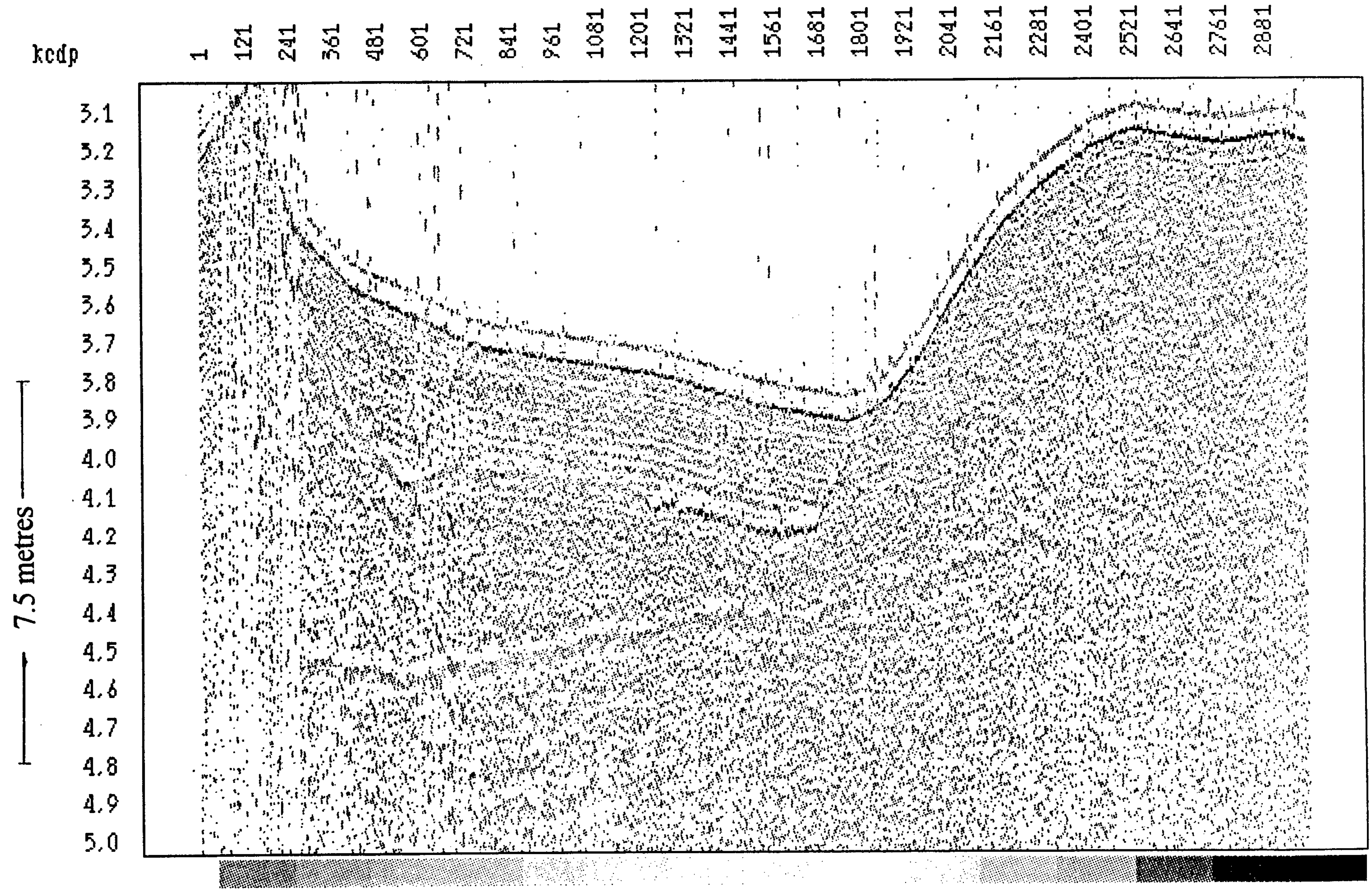


Shear wave velocity profile
Rebecca Shoals area
Vs [m/s]
300
250
200
150
100
50
0
340
360
380
400
420
440
station number
Vs at 0.5 m. depth
Vs at 2.0 m. depth

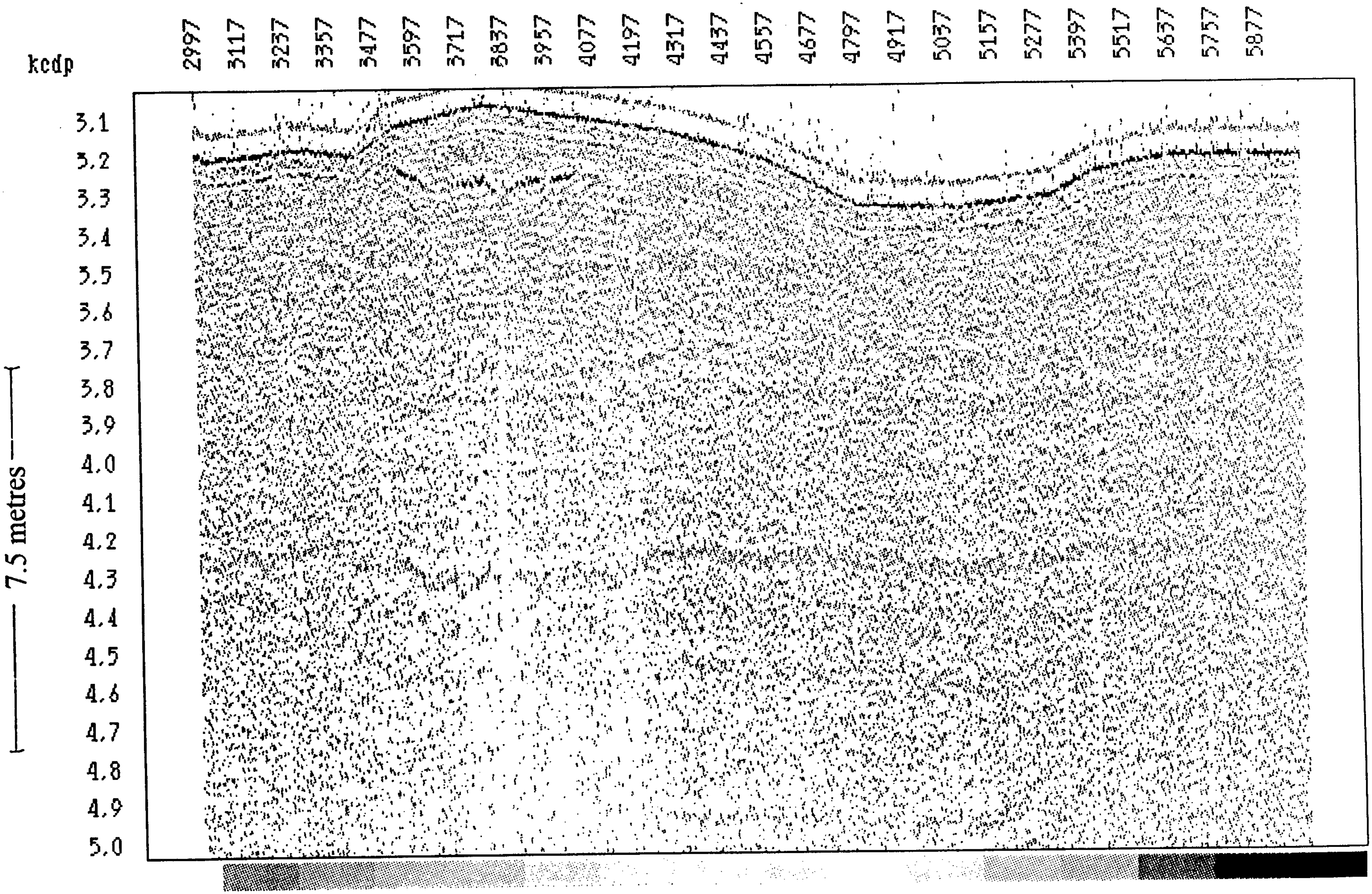
Shear wave velocity-depth profile
[station 369, Rebecca Shoals]



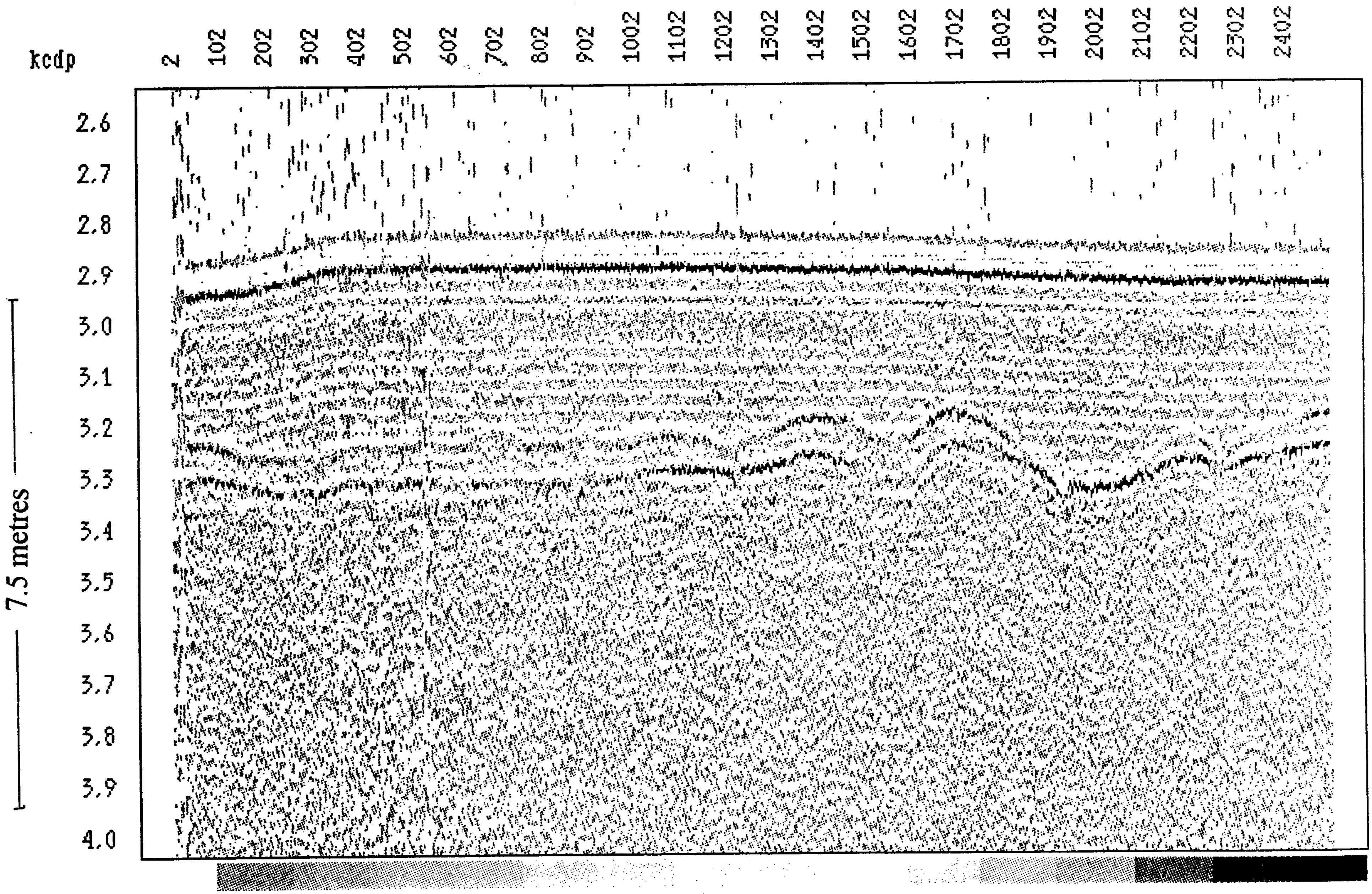

Shear wave velocity gradient profile
Rebecca Shoals area
velocity gradient [(m/s)/m]
0
10
20
30
40
50
60
340
360
380
400
420
440
station number



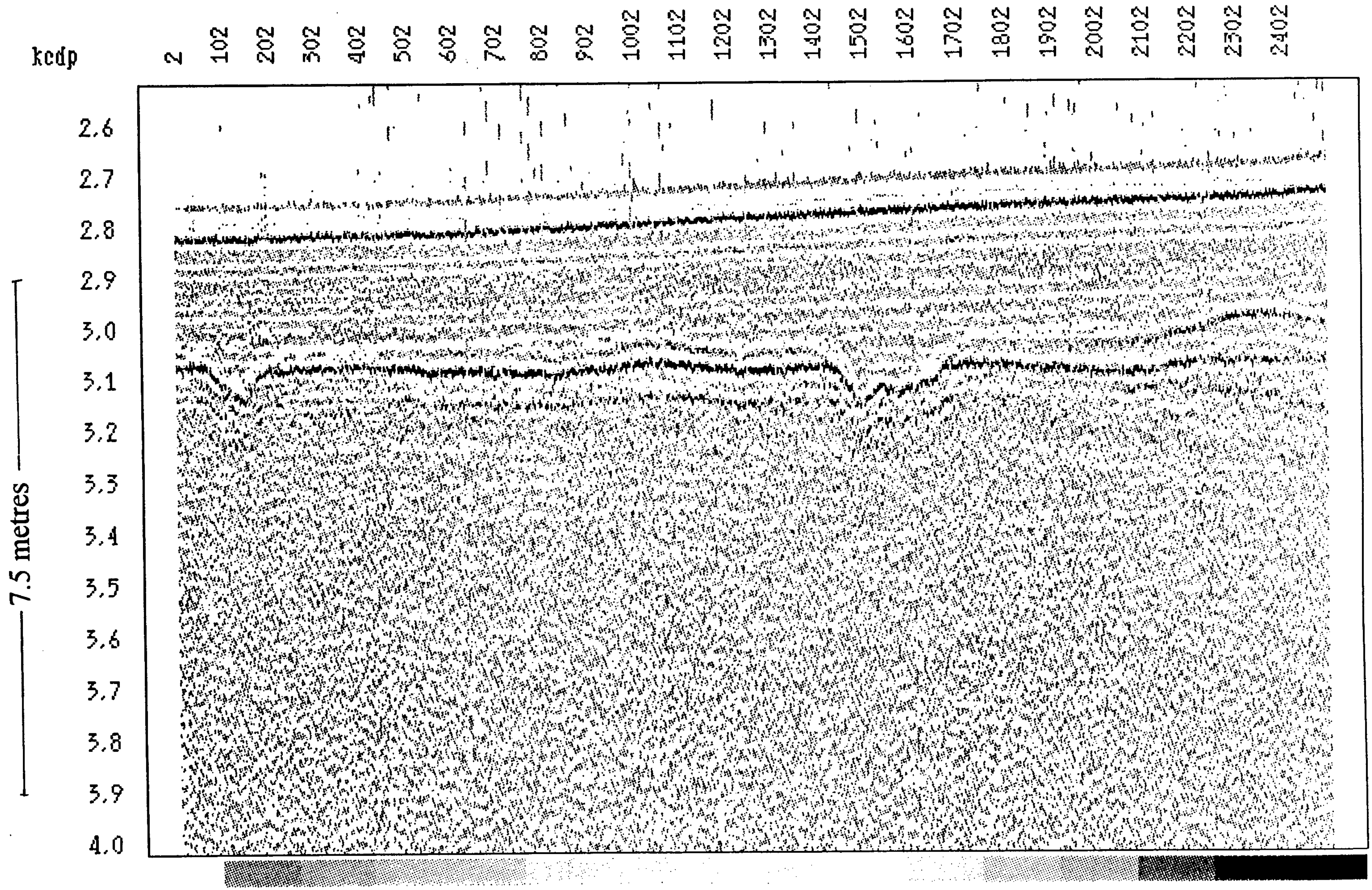
Dry Tortugas Line 26 (Horizontal scale: 100 shots = 100 m)



Dry Tortugas Line 26 (Horizontal scale 100 shots = 100 m)



Marquesas Keys Line 29 (Horizontal scale 100 shots = 100 m)



Marquesas Keys Line 29 (Horizontal scale 100 shots = 100 m)

2.8 Measurement of High-Frequency Acoustic Scattering From Coastal Sediments (Principal Investigators: D.R. Jackson and K.L. Williams)

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Kevin L. Williams
Applied Physics Laboratory, College of Ocean and Fishery Sciences,
University of Washington, Seattle, Washington 98195

INTRODUCTION

The focus of this work is measurement of monostatic and bistatic scattering from shallow water sediments. One objective is to use the scattering data to clarify mechanisms responsible for scattering. Another is to use the backscatter data to acoustically monitor physical and biological processes that affect the seafloor. During FY95, the Key West Campaign was the major effort. Enhancements compared to the Eckernförde and Panama City experiments included the use of a 300 kHz sonar in addition to the 40 kHz sonar used in previous experiments. In addition, mine-like targets were included in the field of view, and improvements were made in bistatic measurement technique. Data analysis efforts in FY95 centered on the Eckernförde and Key West experiments.

RESULTS

Key West Experiment

The APL experiments were carried out aboard R/V Seaward Explorer, during the period 7-26 February 1995. The acoustic measurement platforms included the Benthic Acoustic Measurement System (BAMS, an autonomous, bottom mounted tripod), a ship-deployed steerable platform supporting several different APL and DRA (Defence Research Agency, UK) arrays, and a spar buoy transmitter. Environmental instrumentation included a wave buoy and anemometer and two Sea Bird CTD units, one attached to BAMS and the other used for casts. Sampling, photography, and bottom modification by UW and NRL divers within the field of view of BAMS was an important part of this effort. Accurate diver navigation was accomplished by use of a hand-held magnetic compass with measuring line attached to BAMS, using acoustic targets as benchmarks.

The primary BAMS instruments included the usual circularly scanning 40 kHz sonar and a new 300 kHz sonar. A data link cable with surface buoy was accessed periodically to check the health of BAMS and to download a small portion of the acoustic data. The 40 kHz data show scattering strengths of medium level, typical of an acoustically "soft" bottom (Fig. 1). Backscattering strength at 40 kHz was spatially patchy, with regions of relatively strong scattering having characteristic dimensions of about 4x4 to 16x16 meters (Fig. 2). In contrast, 300 kHz images were relatively uniform (Figure 3, note that the bright ring at about 20 meters range is ocean surface reverberation due to a sonar sidelobe). Correlation processing of successive 40 kHz scans

(Figure 4) shows a moderate rate of activity, with correlation decreasing to 0.87 in a period of 2 days. This rate of decorrelation is intermediate between the slow decorrelation of Eckernförde (correlation 0.96 after 2 days) and the rapid decorrelation of the Panama City site (correlation 0.52 after 2 days). The 50-m radius scan region showed "hot spots" of high activity. One hot spot was found to be a hole about 2.5 ft. in diameter and 1.3 ft. in depth at its deepest point and populated with finger sponges. Experiments were conducted in which divers roughened, smoothed, or otherwise altered the bottom in the field of view of BAMS. Stereophotographs were taken before and after these alterations to quantify changes in microtopography.

Bistatic bottom scattering measurements were made using BAMS as the transmitter at 40 kHz. The receiving array had a horizontal aperture of 1.5 m and was mounted on an azimuthally steerable platform from the stern of the Seaward Explorer with an APL-developed heave compensation device. Data on experimental geometry was continuously logged using the digitized outputs of a compass, inclinometers, acoustic transponder, pressure gauge, and acoustic altimeter. Use of improved methods allowed acquisition of bistatic data on 61 scans, a factor of 4 increase over previous cruises. These data are of higher quality than previously obtained, and the larger number of scans will permit better resolution of the angular dependence of acoustic scattering.

Several targets were deployed in the field of view of BAMS (these are marked in Figures 2-4; not all targets show up in any one type of processing). NRL made repeated photographic dives on these targets to record aspect, burial, and scouring. Figures 5-8 show the peak values found as a function of time for four of these target in the ÒLambertÓ images produced from the experiment. DRA made backscattering and target scattering measurements using two Ònext generationÓ prototype sonars. These sonars were deployed using the ship-board apparatus from the bistatic experiment. Both sonars included transmitter/receiver arrays and both were broadband allowing backscattering and target scattering measurements from 30 kHz to 210 kHz. These measurements complement the measurements from the BAMS tower.

Comparison of Bistatic Data of Eckernförde with Bubble Model

Chu, et al. (1995) have developed a model for bistatic scattering that explicitly treats scattering from a bubble layer in sediments . The model has been compared to the bistatic data acquired at Eckernförde. There is reasonable agreement between experiment and model for the bistatic scattering level as a function azimuthal angle when an equivalent surface scattering strength of 1.4 e+4 bubbles per square meter was used, which is in agreement with the value found in the limited core data collected by Anderson et.al.

Analysis of Eckernförde backscatter data

As previously reported, events observed in the acoustic backscatter data showed suggestive, but inconclusive correlation with oceanographic data, particularly that of Friedrichs and Wright (1995). These early processing efforts led to uncertain results owing to strong stratification of the water column. Changes in the depth of the thermocline (which was at a depth comparable to the sonar transducer) could have been the cause of the observed events, rather than benthic

change. To eliminate this possibility, the lag time for scan-scan correlations has been reduced to a minimum (one hour, which is the scan interval). This greatly reduces water column refractive differences compared to previous processing in which lags of the order 1 week were used.

Short-lag correlation images show impulsive events localized at a few points within the sonar field of view. Interferometric bathymetry processing showed that, simultaneous with these events, the affected pixels underwent large excursions (0.1-10 m) in apparent altitude. This indicates that the acoustic scatterers responsible for the events are in the water column. The central question is the nature of these scatterers; are they pelagic animals, gas bubbles, or some other water-borne scatterer? Our volume scattering data (Jackson, et al., 1996) showed very low levels at Eckernförde in comparison to other sites, suggesting a non-biological cause.

Subsequent processing centered on the issue of spatial localization of the scatterers, which would not be characteristic of pelagic animals or drifting, water-borne scatterers. The correlation processing used with these data could produce such localization as an artifact. This artifact might occur when a water-borne scatterer passes over a portion of the sea floor from which the normally occurring backscattered signal is weak. Such events yield abnormally low correlation, as the water-borne scatterer does not have to compete with a strong sea floor return. A new processing algorithm was developed to reduce this artifact. In this algorithm, the decorrelation (1 - correlation) is multiplied by the signal intensity and the product is converted to target strength units. The upper panel of Fig. 9 shows the spatial distribution of events defined by a target strength threshold of -40 dB (for reference, this is the approximate target strength of a small fish or 4 cm gas bubble). This picture does not exhibit strong localization; that is, the frequency of events in pixels can be fitted by a Poisson distribution. In the next stage of processing, an additional event selection criterion was applied, namely, that the altitude should undergo a substantial excursion (as would be the case for scatterers in the water column). Note that this criterion can be reversed to study events at or in the sea floor. The lower panel of Fig. 9 shows the events having target strength greater than -45 dB and apparent altitude change greater than 0.5 m. This selection has thinned out the events considerably and produced spatial localization.

If the scatterers in question are randomly distributed in space, the distribution of events would be Poisson. Figure 10 shows that the data do fit a Poisson distribution, even though spatially localized. That is, the number of pixels with 0, 1, 2, etc. events follows a Poisson distribution for reasons that are not clear at present. We are working with Wright and Friedrichs at VIMS and Wever at FWG to understand the physical cause or causes of the observed events. The best evidence that the events have oceanographic significance is displayed in Fig. 11. In this figure, the target strength time series formed for the events of the lower panel of Fig. 9 is compared with the time series for pressure at the seafloor, including air pressure (Data obtained by Wever and Abegg, sea level data from Wasser- und Schiffahrtsdirektion (WSD) Nord, Kiel). The correlation of the events with episodes of reduced pressure suggests gas ebullition as the cause. It should be noted that the acoustic data only cover the time interval 3.5 - 16 days, so the absence of events near at the early and late parts of the record has no significance.

Preliminary Conclusions

Our bistatic scattering data from Eckernförde support the bubble scattering model of Chu, et al. (1995). This strengthens the picture developed by Tang, et al. (1994) based on altimetry processing of our 40 kHz data. The backscatter data from Eckernförde show sporadic, localized events that may be associated with frequent gas ebullition.

Significance of Results to CBBL objectives

The results obtained to date address CBBL objectives at two levels. First, the acoustic data have provided a means of monitoring biological and physical processes over relatively large regions and time spans (as compared to point sampling). Interesting acoustic phenomena that are environmentally driven have been observed, notably, extremely rapid acoustic change at the Panama City site and impulsive events at Eckernförde Bay. Second, the data have been used to better understand the acoustic scattering mechanisms and their relation to environmental forcing. The physical model for scattering from bubbles at Eckernförde as developed by Tang and colleagues is the best example to date.

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Chu, D. , Tang, D., Jackson, D. R., and Williams, K. (1995) "High-frequency bistatic scattering by sub-bottom gas bubbles," Journal of the Acoustical Society of America, Vol. 98, 2987

Friedrichs, C. T. and Wright, L. D. (1995) "Resonant internal waves and their role in transport and accumulation of fine sediment in Eckernförde Bay, Baltic Sea," Continental Shelf Research, Vol. 15, 1697-1721

Jackson, D. R., Williams, K. L., and Briggs, K. B. (1995) "High-frequency observations of benthic spatial and temporal variability,", Geomarine Letters (accepted).

Tang, D., Jin, G., Jackson, D. R., and Williams, K. l. (1994) Analysis of high-frequency bottom and sub-bottom backscattering for two distinct shallow water sites. Journal of the Acoustical Society of America, Vol. 96, 2930-2936.

Accomplishments Over Past 3 Years

Acquired large, high-quality bistatic and monostatic acoustic scattering data sets from well-characterized sites

In collaboration with Tang and colleagues, verified their bubble scattering model

Measured rate of acoustic change at three sites with time scales varying by two orders of magnitude

Demonstrated that scattering at Panama City site is a surficial process

Measured spatial and temporal frequency of pressure-driven changes in gaseous methane at Eckernförde

Publications and PRESENTATIONS resulting from this work

Briggs, K. B., Richardson, M. D., Jackson, D. R., (1994) "High-frequency bottom backscattering from a gassy mud," J. Acoust. Soc. Am. Vol. 96, 3218

Chu, D. , Tang, D., Jackson, D.R., and Williams, K. (1995), "High-frequency bistatic scattering by sub-bottom gas bubbles," Journal of the Acoustical Society of America, Vol. 98, 2987

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Jackson, D. R., Wright, L. D., (1994) " Influence of sediment transport events upon bottom backscattering, Eckernförde Bay," J. Acoust. Soc. Am., Vol. 96, 3247.

Tang, D., Jin, G., Jackson, D.R., and Williams, K. (1994) Analysis of high-frequency bottom and sub-bottom backscattering for two distinct shallow water sites. Journal of the Acoustical Society of America, Vol. 96, 2930-2936.

Williams, K. L., Jackson, D. R., (1994) "Bistatic bottom scattering at high frequencies: Experiment and model comparison," J. Acoust. Soc. Am. Vol. 96, 3286.

Williams, K. L., Dahl, P. H. , Jackson, D. R., (1994) "Some current efforts and future plans in surface and bottom scattering characterization (U)," Proceedings of The Technical Cooperation Program

Williams, K. L., Jackson, D. R., (1994) "Monostatic and bistatic bottom scattering: Recent experiments and modeling,Ó Proceedings of Oceans "94"

Williams, K. L. and Jackson, D. R. (1995), "Acoustic scattering measurements at 40 kHz," Proceedings of the Workshop, Modelling Methane-Rich Sediments of Eckernförde Bay, T. Wever, Ed., FWG Report 22, 97-100.

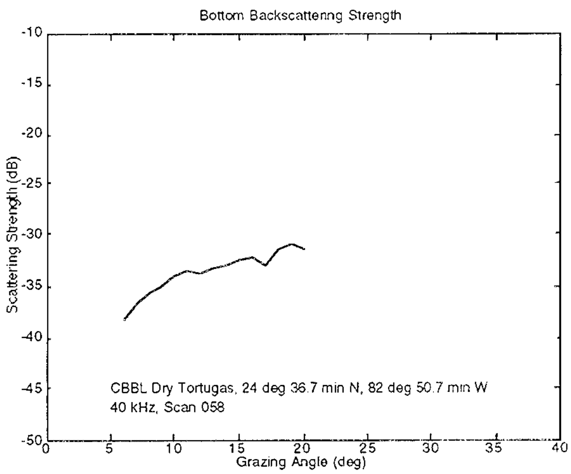


Figure 1. Backscattering strength at 40 kHz in the vicinity of the BAMS tower during the Key West experiment

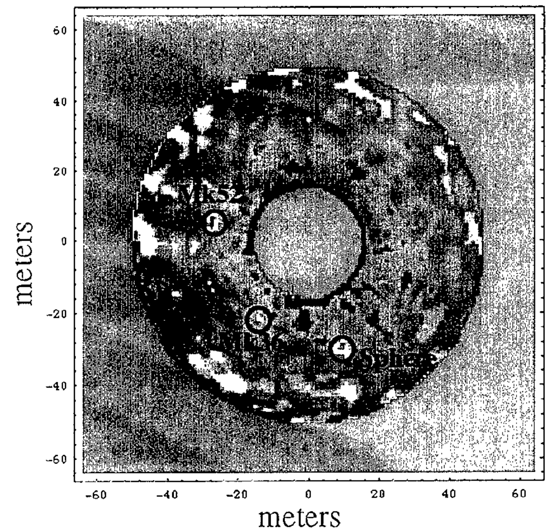


Figure 2. Image of Lambert scattering parameter at 40 kHz in the vicinity of BAMS. Color progression is violet, blue, green, yellow, and red as one goes from low to high scattering strengths. The two red regions are artificial targets.

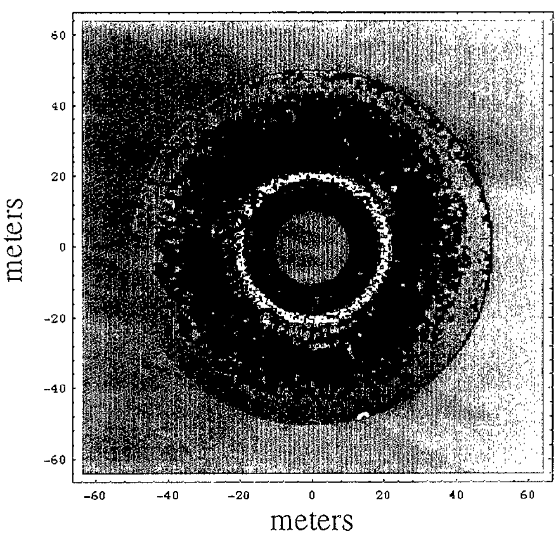


Figure 3. Image of the Lambert scattering parameter at 300 kHz. The locations of some of the targets are shown. The ring of high scattering in the figure is due to a sidelobe scattering near normal incidence from the ocean air/water interface

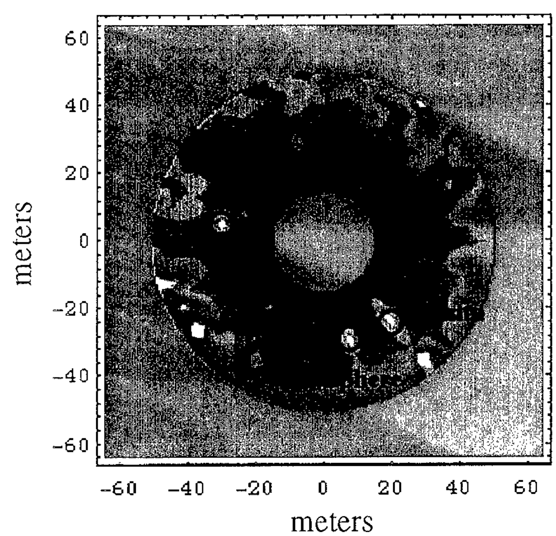


Figure 4. Correlation between two BAMS scans twelve hours apart. Colors go from blue-green-yellow-red as correlation goes from 1.0 to 0.5. The Manta mine, which is not detectable in scattering images of Figures 2 and 3 shows up in this correlation image.

Figure 5

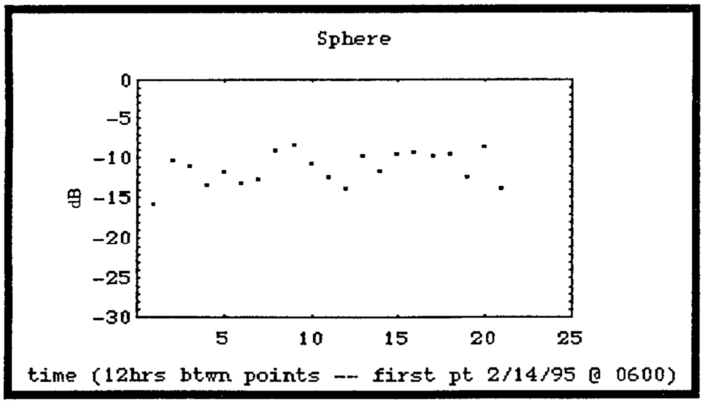
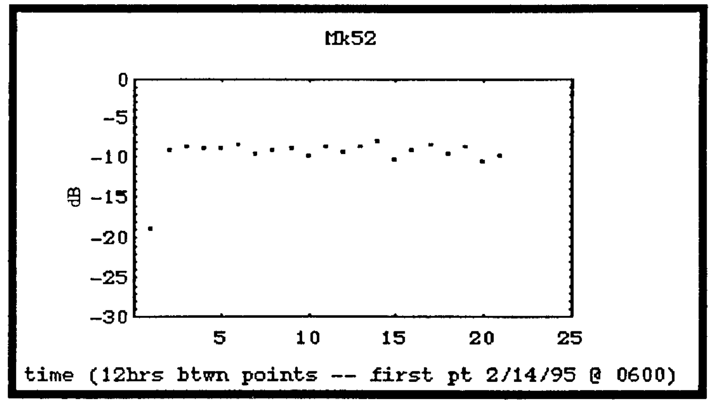


Figure 6



These figures show the peak values found for each target in the "Lambert" images produced from the experiment. In Lambert images spherical spreading and incident angle dependence (based on Lambert scattering assumption) are removed so as to get a scattering strength image with little mean change as a function of range.There is approximately 12 hours between data points, the data thus represent about 10.5 days from 2/14/95 @ 0600 local time to 2/24/95 @ 1800. The oscillations seen in the sphere data can be accounted for by the fact that it is tethered 2 meters above the bottom and so moves in correspondence with water currents. The mean level for the sphere, Mk 52, and Destructor does not change significantly with time. The mean level for the MK 36 has an upward trend through the time period of the experiment.

Figure 7

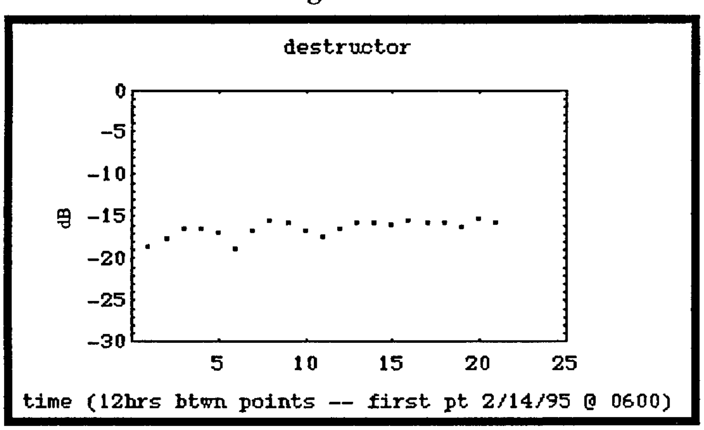
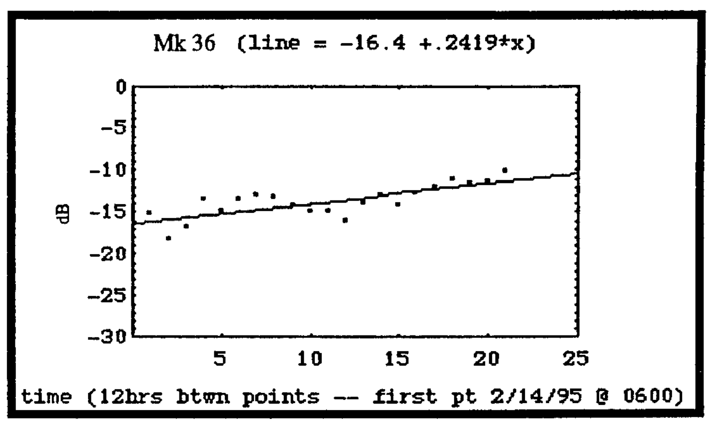
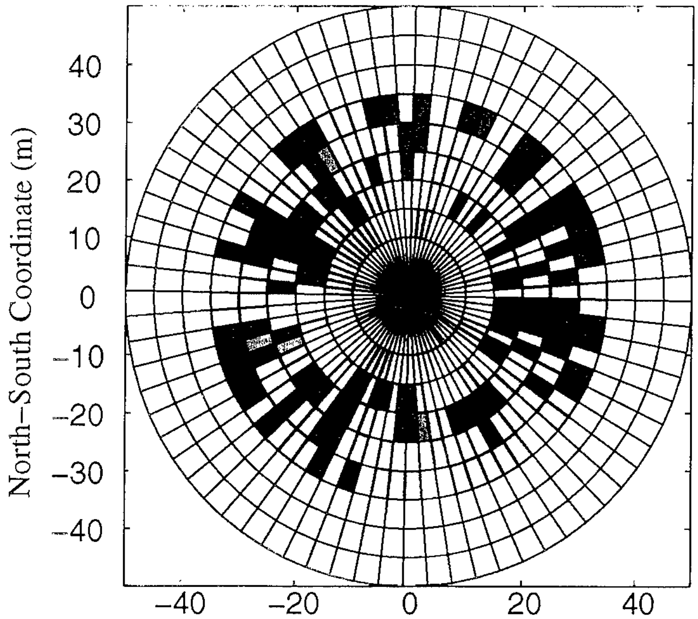
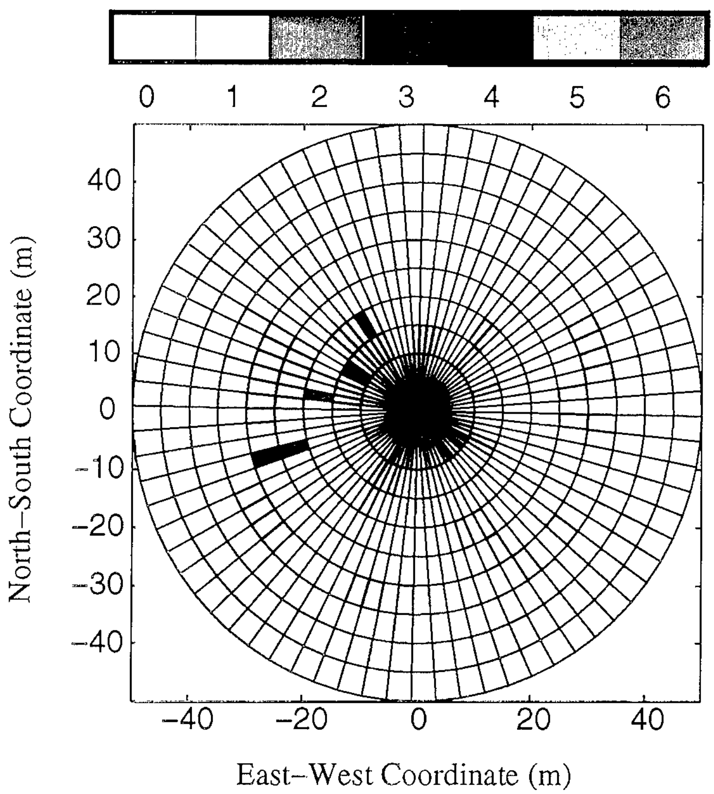


Figure 8





Target Strength Events, Thresh = −40 dB, Eckernfoerde First Deployment



Combined Events, Thresh = −45 dB, 0.5 m, Eckernfoerde First Deployment

Figure 9. Comparison of events exceeding a given target strength threshold without (top) and with (bottom) a condition on altitude change.

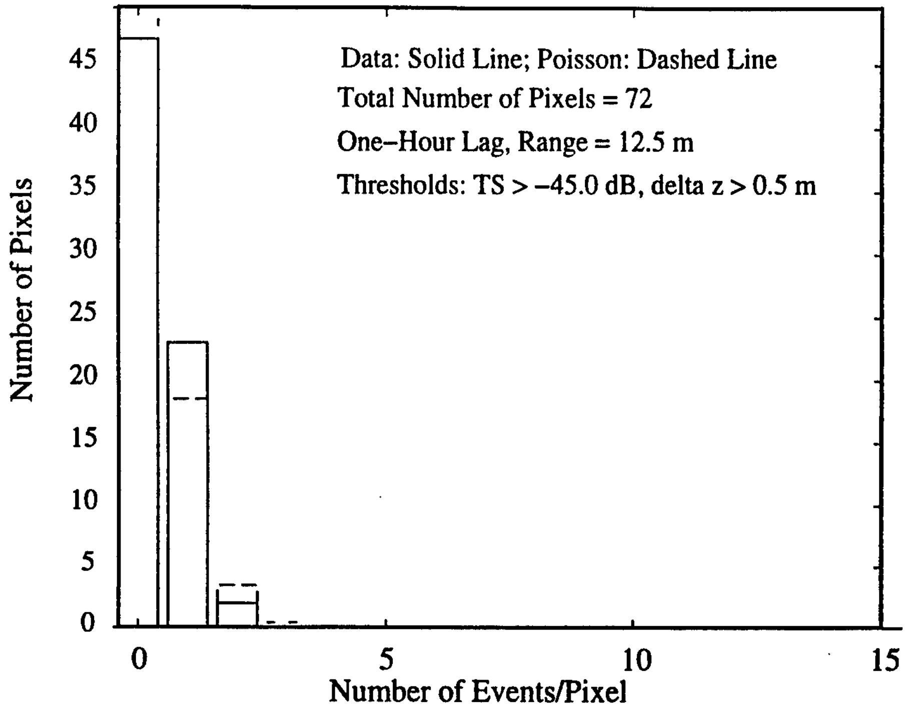


Figure 10. Histogram of Events, Eckernfoerde First Deployment

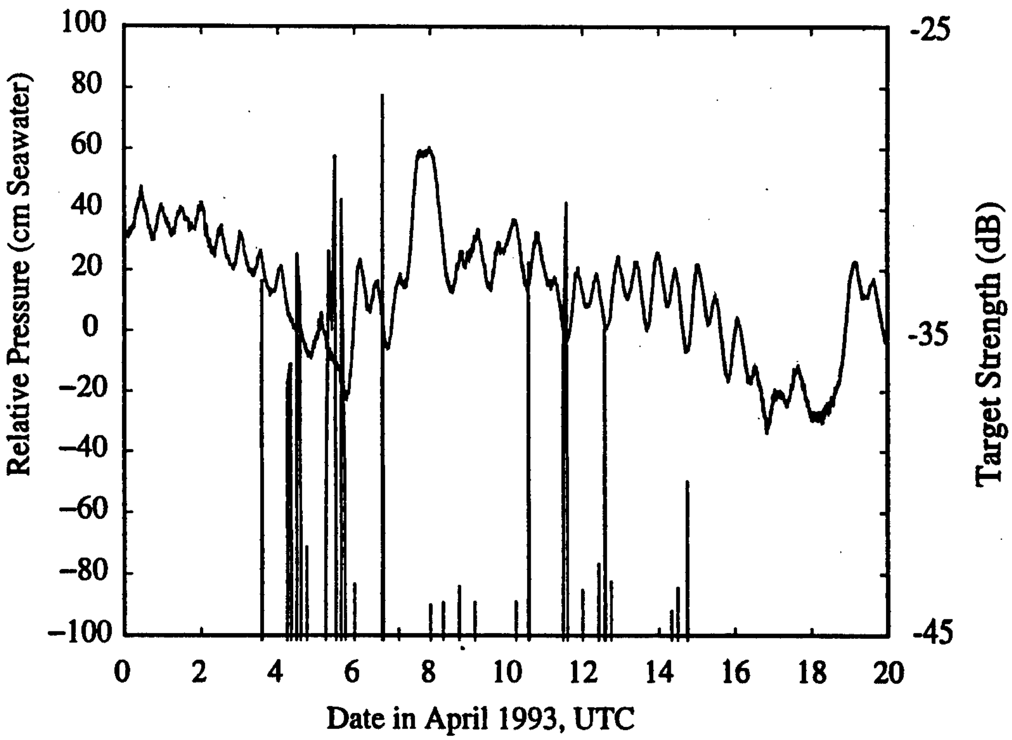


Figure 11. Seafloor Pressure and Target Strength, Eckernfoerde First Deployment

2.9 Quantification of High Frequency Acoustic Response to Seafloor Micromorphology in Shallow Water (Principal Investigators: D.N. Lambert, D.J. Walter, D.C. Young and J.A. Hawkins)

D.N. Lambert[1], D.J. Walter[1], D.C. Young[1], and J.A. Hawkins[2]

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Project Objectives

The overall objectives of this project are (1) to investigate new methods of quantifying the effect of sediment micromorphologic structure on high frequency acoustic response in shallow water and its relationship to in situ acoustic and geotechnical properties and (2) to provide a 3-D digital high resolution micromorphologic characterization of the various CBBL program experimental sites.

Introduction

During FY95, a significant portion of the high resolution ASCS data previously collected FY93 and FY94 off Eckernförde, Germany in the Baltic sea was analyzed and compared to ground truth core and in situ probe data. Results of these studies have been presented at several conferences and in publications. ASCS data from this area has also been distributed to a number of other CBBL investigators for specific modeling and correlative studies. The objective of developing an improved, more accurate method for predicting sediment acoustic impedance and thus, sediment geotechnical properties, was continued with promising initial results. These results led to additional FY95 6.1 funding to conduct a proof of concept study of two promising inversion techniques. This spin-off project was completed at the end of FY95 with a new linear least square inversion method being developed (Wood and Lindwall, in press). This technique appears to make more accurate and continuous profiles of sediment acoustic impedance. In addition, the ASCS team spent the month of February working simultaneously from two ships collecting ASCS data at several frequencies in order to acoustically characterize the Dry Tortugas, Marquesas, and Quicksands (Half Moon Shoal) primary study areas off Key West, Florida (Fig. 1). The ASCS team also collected acoustic data for three other related research projects during this field work. An additional investigation dealing with spectral ratios of bubbly sediments has been successful in exploiting the frequency dependent behavior of these sediments as an acoustic signature for the routine identification of bubbly sediments with acoustic profilers (Hawkins, et. al., submitted).

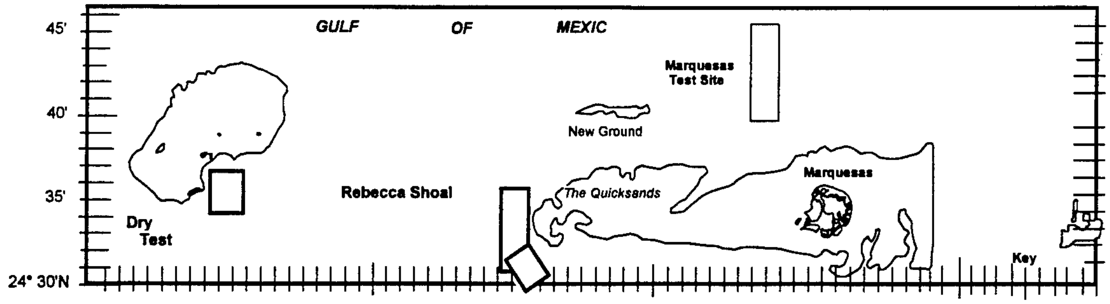

Figure 1. General map of the shallow water areas west of Key West, FL showing the location of the 1995 CBBL test sites.

Current Status and Progress

During a three week cruise in January and February 1994, the ASCS team collected 15 kHz subbottom data over a large expanse of the navigable shallow water areas west of Key West. This data was then used to delineate potential areas that would be suitable for use as the test sites for the planned FY95 CBBL experiment. An area north of the Marquesas Keys and an area south of Garden Key in the Dry Tortugas were determined to be the most suitable soft sediment sites. The Dry Tortugas area was later chosen as the primary acoustic test site since it is more protected from winter storms. A sand ridge area west of the Quicksands near Half Moon Shoal was chosen as the coarse grained sediment experiment site.

During the FY95 CBBL experiment, ASCS data was collected simultaneously from two ships using five different transducers, several different frequencies and using several methods of deployment. From the WFS PLANET, an EDO 6991 transducer was hard mounted inside the ship's transducer well. This method had been used several times previously on field trips in the Baltic Sea and found to be an excellent method of deployment due to the stability and quietness of this 80 meter long ship. In this configuration, the EDO transducer was used primarily at 15 kHz with a 12^{o} beamwidth although it was operated at 30 kHz for a short period of time. In the Dry Tortugas study area, the PLANET ran north-south tracklines over this 3 by 3 nautical mile area. A trackline spacing of approximately 105 meters ensured overlapping coverage of 100 kHz side scan sonar swaths run simultaneously with the ASCS (Fig. 2). The side scan data and ASCS data correlated extremely well over the Dry Tortugas study area where the seafloor varied from soft carbonate muds to sands, to bare rock, and live coral reef.

On the RV SEWARD JOHNSON, 15 kHz data was collected using an ELAC LSE-179 transducer gimbal mounted in an Endeco tow-body during the first leg general survey portion of the cruise. Because the tow-body could not be deployed at the same time as other over the side operations, ASCS data was collected through a ships hull mounted 3.5 kHz transducer array (12 transducers) during the second and third legs. It was found that this array had a slightly better acoustic response at 4 kHz, thus, it was operated at this frequency. Overall, data collected with this transducer array turned out to be excellent and delineated the sediment column in the area extremely well. The ship also had a hull mounted 12 kHz transducer that was similar to the

Navy's standard UQN-4 fathometer transducer. This transducer was also operated during the cruise with the data collected used primarily for the MTEDS demonstration project which was conducted during a portion of the second leg of the cruise.. An ITC 50 kHz transducer was operated exclusively by hanging it over the side of the ship while the ship was occupying sampling stations collecting sediment cores, eXpendable Doppler Penetrometer (XDP) data, piezocone data and density probe data. Using this method, a minimum of 150 pings of 50 kHz data was collected at nearly all of the core, XDP, and piezocone stations. In addition, 4 kHz data was also collected at each of these stations. Color ASCS subbottom records of these ground truth sites have been provided to all CBBL investigators requesting them.

Figure 3 is an example of a series of survey tracklines run in the Tortugas study area from the SEWARD JOHNSON. In this illustration, the frequency of the data collected is 4 kHz and the trackline spacing of both the north-south and east-west tracks is 0.5 nautical mile. These same tracklines were also run at 12 kHz and 15 kHz. Figure 4 is the series of seven north-south 4 kHz seismic profiles shown as tracklines in Figure 3. The dominate feature in these records is the submerged Pleistocene Key Largo limestone which forms the sedimentary basement throughout the area. It is shown as the yellow to red undulating reflector beneath the unconsolidated sediments. It is also exposed at the seafloor surface or underlies thin veneers of sand and reef rubble over significant portions of the area. It also provides the hardground on which the present day live reefs are attached. Figure 5 is a 4 kHz east west seismic record across the Torgugas test site. Note the unconsolidated sediment pond between the two reefs in the center and right portion of the illustration. Over the live reefs, the record shows low reflectivity, irregular returns above the underlying bedrock which forms the reef base. These "fuzzy" low reflectivity structures are acoustic returns from the corals, sea fans, and gorgonians which make up the live portions of the reef. Note that the reef in the center of this record has a smooth seaward face, probably covered by a veneer of sand while the shoreward face appears rougher, probably due to rubble with some live reef components attached. At the very left of the record is a Pleistocene channel cut in the Key Largo limestone which has been buried by Holocene sediments.

Figures 6 and 7 are south to north (left to right) 4 kHz ASCS profiles across two areas of the Honeymoon Shoal sand wave area. These sand waves are tidal current driven and were observed up to 7 m in amplitude with 3 - 4 m more typical. In the southern most profile (Fig. 6) the thickness of the sand sediment averages 6 - 7 m over the Key Largo Limestone. The sand waves are composed of singular crests with a period averaging approximately 100 m. The sand thickness gradually thins to the north indicating that the net sediment transport in the area is to the south. In Figure 7 shows a transition from steep sided single crested sand waves with amplitudes of 3 - 4 m on the south into smaller amplitude waves with multiple crests. Note that the sand thickness changes from 3 -4 m thick on the south to approximately only one meter in thickness on the north. A short distance to the north, the sand waves disappear as the Key :Largo Limestone is exposed at the sediment water interface.

The Marquesas Study area is depicted in Figures 8 and 9. Figure 8 is a 15 kHz south to north (left to right) profile across the southern boundary of the area showing the transition from Key Largo Limestone exposed at the sediment-water interface to onlapping Holocene carbonate muds. In the center of the profile, the Key Largo formation can bee seen at the reflector

approximately four meters below sediment surface. In this area, the water becomes slightly deeper north. Sediments also become slightly thicker to the north. Figure 9 is a typical subbottom profile in the Marquesas area. Unconsolidated sediment thickness is four to five meters thick. The higher reflectivity discontinuous layers and common "hot spots" are thought to be concentrations of shell material.

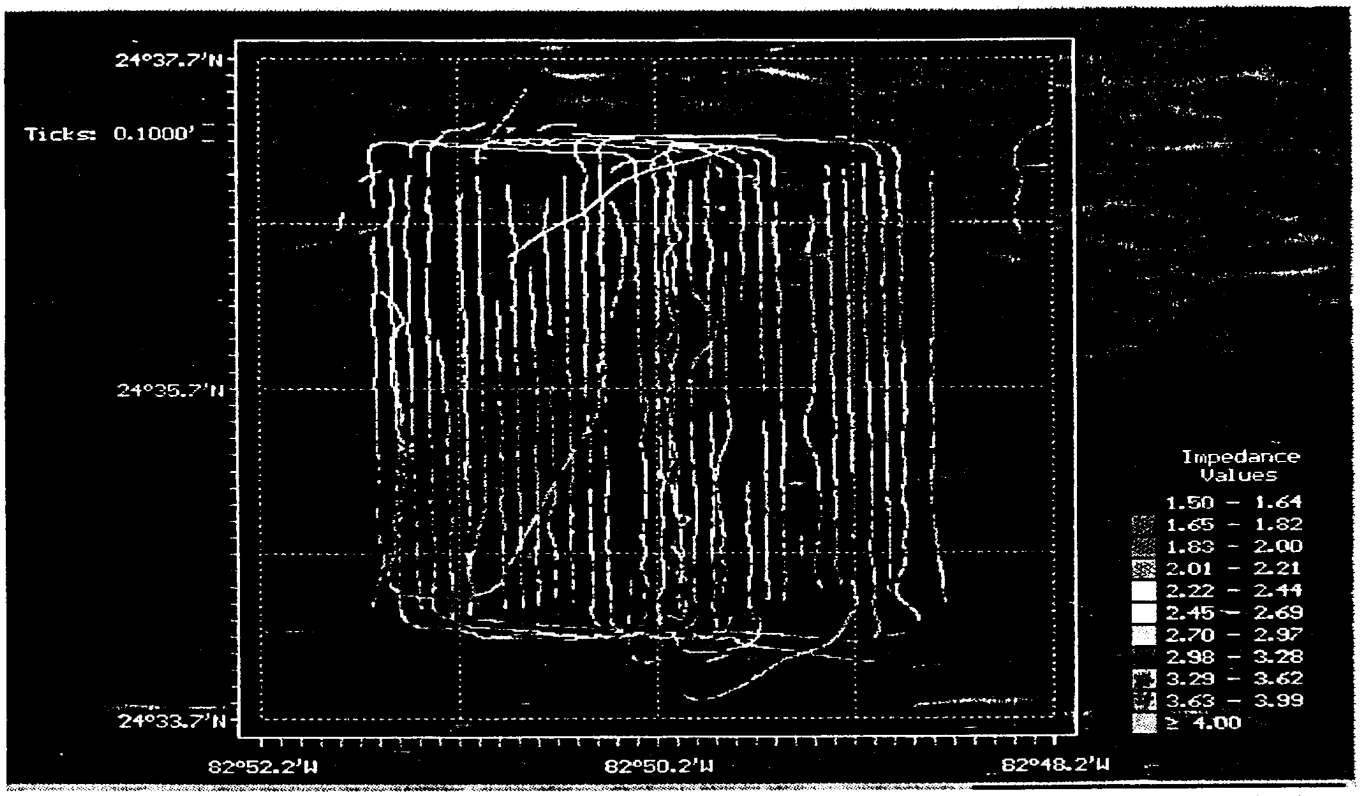

Figure 2. 15 kHz survey tracklines run by the WFS PLANET during Leg 1 of the CBBL cruise in the Southeast Channel off Garden Key, Dry Tortugas, FL. The lines represent the geographic position and color coded impedance of the surficial sediment layer (0 - 40 cm increment) predicted by NRL ASCS.

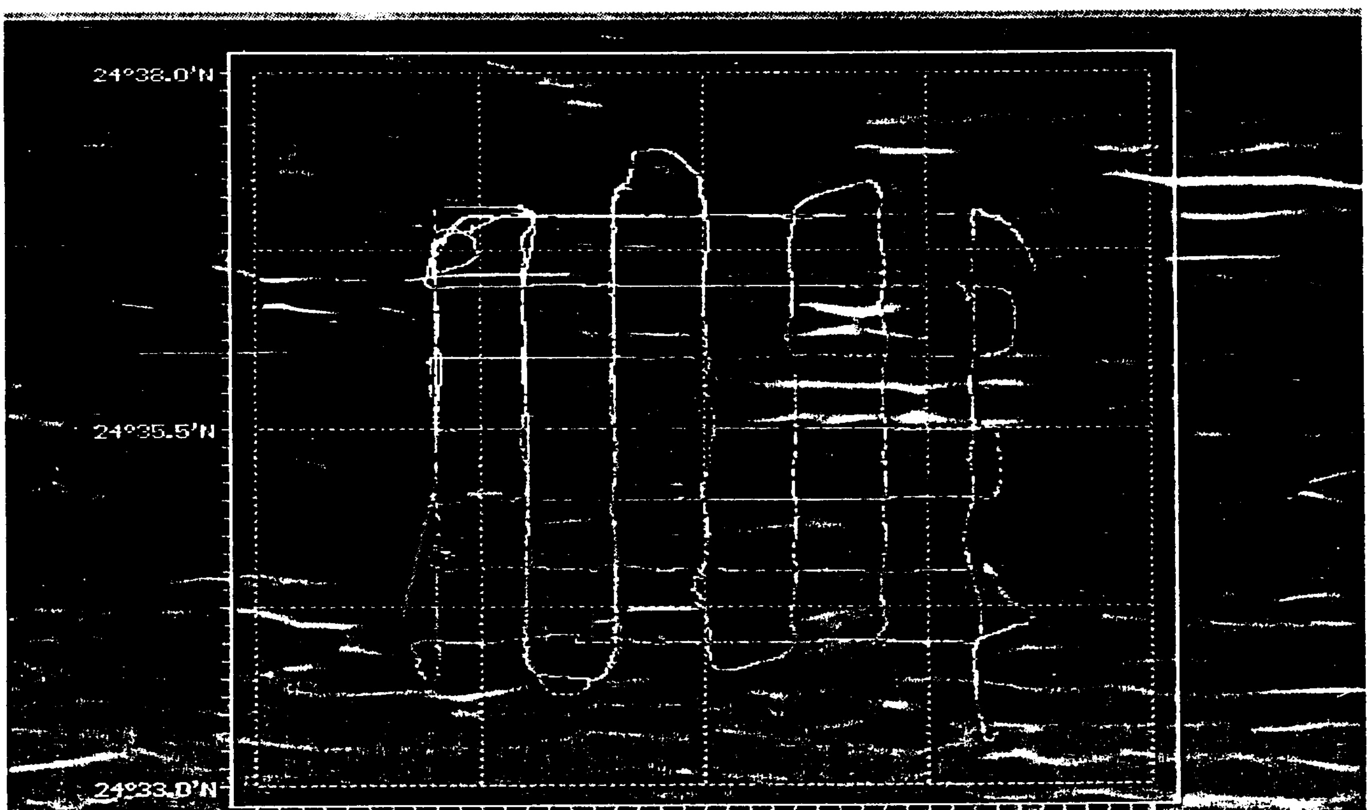

Figure 3. Tracklines run by R/V Seward Johnson during Leg 2 of CBBL cruise in Southeast Channel off Garden Key., Dry Tortugas, Florida. Lines represent location and color coded impedance of surficial sediment (0 - 80 cm increment) predicted by the NRL ASCS operating at 4 kHz.

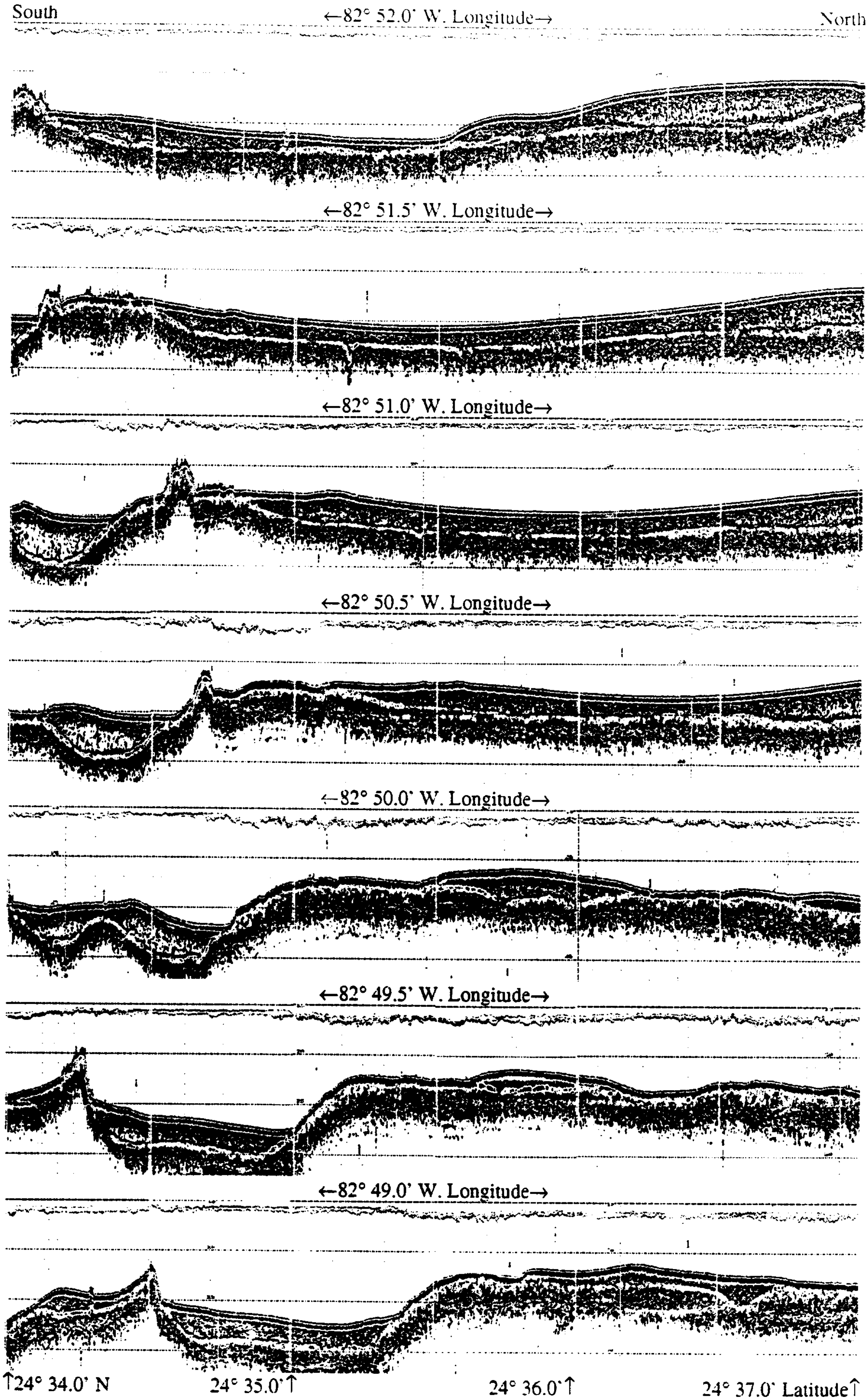

Figure 4. North-South ASCS 4 kHz subbottom profiles across the CBBL Dry Tortugas study area. Trackline spacing is 0.5 nautical mile.

DRY TORTUGAS ASCS LINE 58 - 59

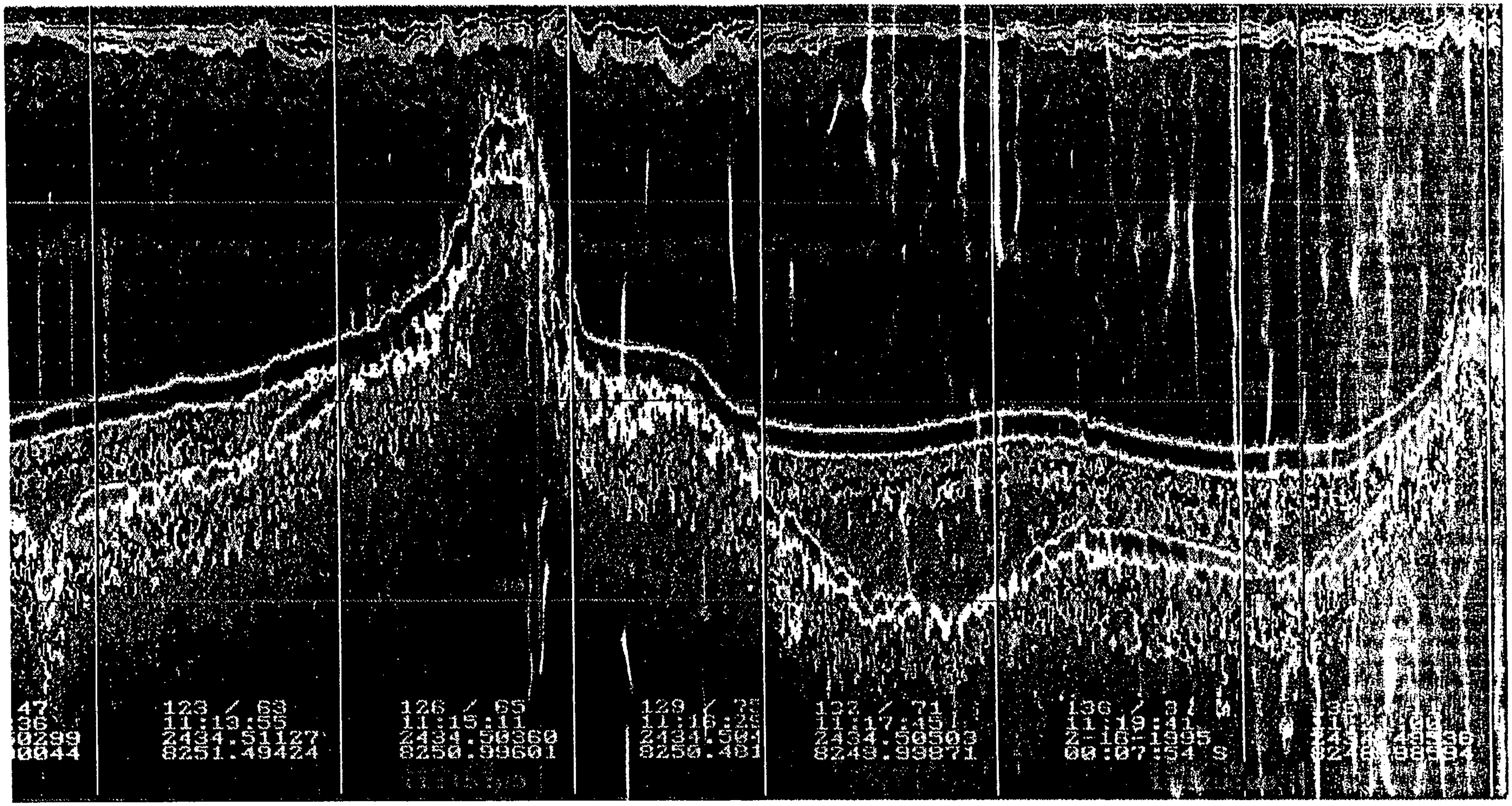

Figure 5. This illustration depicts a 3 nmi long east-west 4 kHz high resolution seismic record across southern portion of the Dry Tortugas CBBL Test Area at 24^{0} 34.5' N latitude. Hot colors (red, yellow, etc.) below the sediment-water interface indicate high reflectivity from sand and rock. Cool colors (blue, green, brown, etc.) indicate low reflectivity or soft muddy sediments. The major sediment structure in this illustration is the Key Largo Limestone formation which is shown as the continuous red/yellow irregular undulating reflector located 1 - 4 m below the sediment surface. It is exposed at the seafloor surface in the left center and far right portions of the record where it forms the base of present day live reefs. In the right center, it underlies a large sediment pond of soft carbonate muds. The sediment deposited over the Key Largo Limestone is mostly carbonate mud that grades to sand west of the reef. Sediment thickness varies from near zero at the reefs to 4 m in the sediment pond. The fuzzy looking structures (lt. blue color) above the reefs are due to sea fans, corals, and gorgonians.

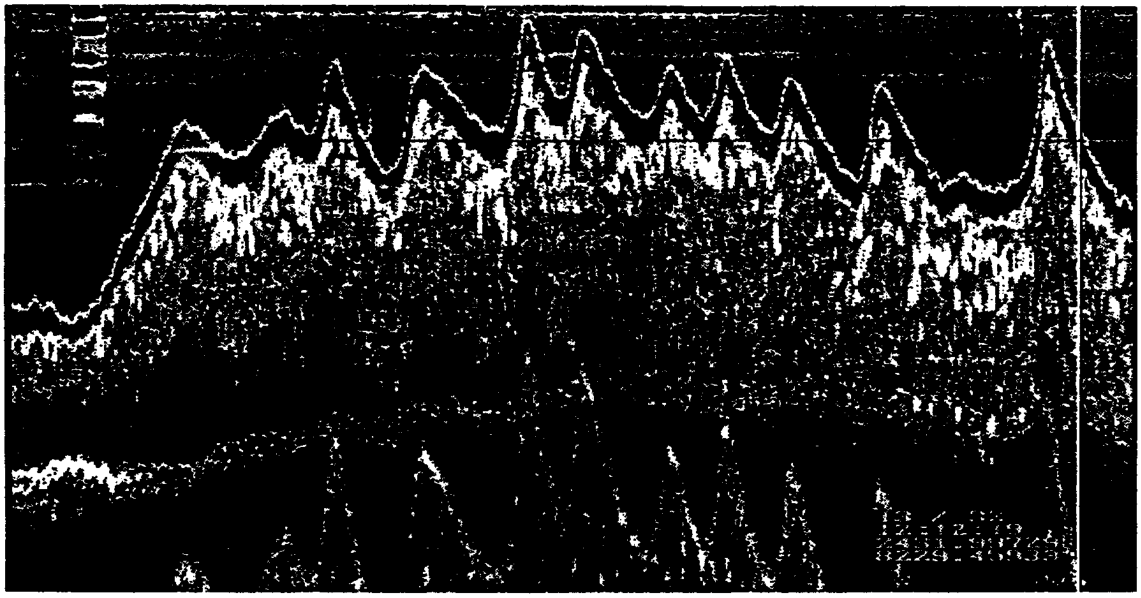

Figure 6. Southern end of tidal current driven sand waves along a south to north trackline west of Half Moon Shoal on the Quicksands. Sand waves were observed up to 7 m in amplitude with 3 - 4 m more typical. The ASCS data is 4 kHz collected using the SEWARD JOHNSON's hull mounted array. The Key Largo Limestone formation can be seen as the undulating green to yellow layer 6 - 7 m below the sand waves. The undulating appearance to this limestone surface is due to sound speed differences through the crests and troughs of the sand waves. Approximate position is 24° 32.0'N, 82° 29.5'W.

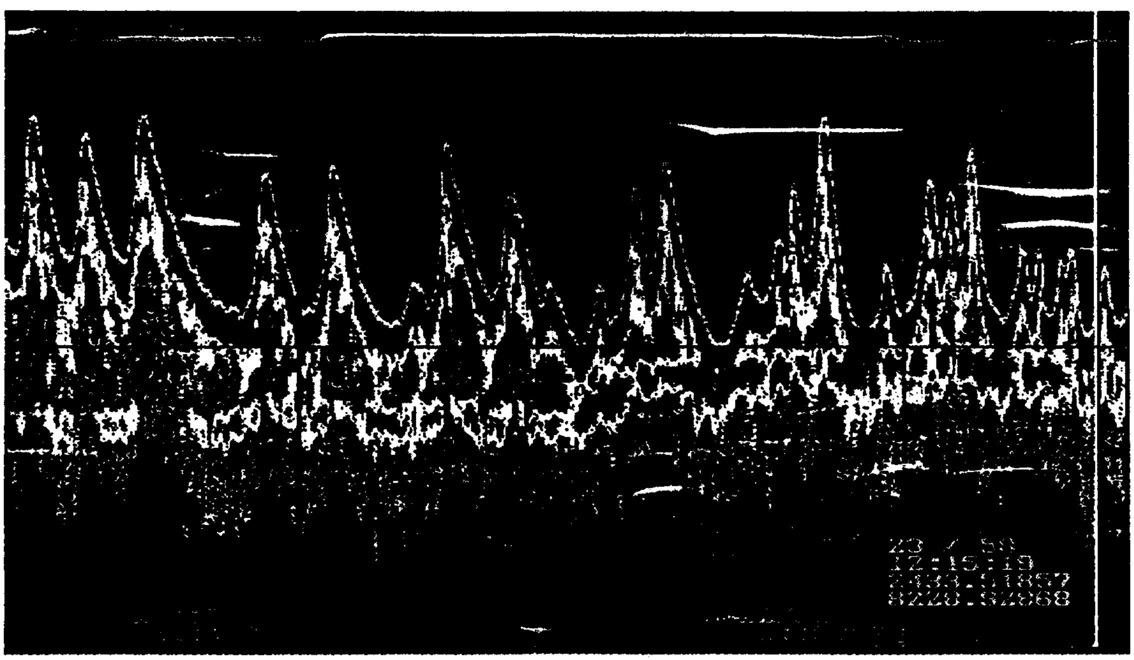

Figure 7. Central portion of tidal current driven sand waves along a south to north trackline west of Half Moon Shoal on the Quicksands. Sand waves here transition from single crests to multiple smaller sand waves superimposed on larger sand waves. The ASCS data is 4 kHz collected using the SEWARD JOHNSON's hull mounted array. The Key Largo Limestone formation can be seen as the undulating red to yellow layer 1 - 2 m below the sand waves. A short distance to the north, the sand waves disappear as the Key Largo Limestone is exposed at the sediment water interface. Approximate position is 24° 33.5'N, 82° 28.9'W.

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2.10 Effects of Environmental Processes on Shear Modulus (Principal Investigators: D. Lavoie and Y. Furukawa)

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INTRODUCTION

This report summarizes the work done under this project as part of the Coastal Benthic Boundary Layer Special Research Program during FY95. This is an ongoing project and we are still striving to meet our original goals which were to (1) continue to investigate gradients of shear modulus in the field on the cm scale using a duomorph probe, (2) examine shear modulus as a function of direction in the field and in the laboratory in our instrumented triaxial cells where the shear and compressional wave velocity can be measured with the three principle stresses carefully controlled, and (3) relate in-situ shear modulus with other geotechnical properties and microstructure. Because these properties are very much controlled by geochemical processes and physical reworking, especially in carbonate sediments such as the Key West environment, we also plan to (4) develop and test a method to correlate the extent of submarine diagenesis to mineralogy, porewater chemistry and microfabric in carbonate sediments, and (5) correlate the extent of reworking to mineralogy, isotope data, porewater chemistry and microfabric.

PROGRESS

Eckernförde Bay

Part of our resources from this project were spent building and improving the DIAS system to measure in situ shear modulus. The DIAS system was deployed in Eckernförde Bay in FY95 with results similar to those achieved in FY94 (see FY94 year end report; Lavoie et al., 1996). In addition to in situ measurements, laboratory physical properties measurements were made in order to collaborate with Bennett and others in correlating microfabric and physical properties; this work is summarized in Lavoie et al, 1996.

One of the important results of the microfabric study is that, unlike other marine sediments, bulk permeability in Eckernförde Bay sediment is probably related to the large-scale pores and channels than to the total porosity. The sediment around the Planet Site is heavily pelletized and the channels around the pellets, probably responsible for the high permeability of this sediment, also influences the rapid dissipation of induced overpressure seen in the piezometer results (see Bennett et al., 1995, this volume). In this respect, and in the shear modulus results, the sediment behaved as one having a coarser grain size than that indicated by the grain size analysis. The

structure suggests that permeabilities should also be slower in the aggregates, which may have implications for the geochemistry and diagenesis of this sediment.

Key West Campaign

A significant effort was made in the FY95 Key West experiment to collect in situ data, cores for later laboratory analyses, box cores for pore water analyses, and undisturbed samples for microfabric.

In situ measurements

The DIAS and ISSAMS systems were deployed at numerous locations in the Dry Tortugas and Marquesas. For methodology, see Lavoie et al., 1996 and Richardson and Briggs, 1996. The results are presented on Fig. 1 and indicate that the values measured using the in situ probes agree well with the values predicted by Bryan and Stoll (1988) to ~75 or 80 cmbsf. Divergence between measured and predicted values below that depth may be caused by scattering off the dense shell layer. Below 100 cm where the shell size and density decrease, measured and predicted values of shear wave velocity begin to converge.

Laboratory measurements

Shear wave velocity measured on cores using the Hamilton frame with shear wave transducers at ambient laboratory pressures is lower than either the predicted values (Bryan and Stoll, 1988) or the in situ measured values (Fig. 2). This suggests that shear wave velocity should be measured at in situ pressures to achieve valid data. We are currently utilizing instrumented triaxial cells and consolidometers for this purpose.

Compressional wave velocity was measured on all cores using the TAMU core logger and reveals very little change in velocity within the upper 2 mbsf (Fig. 3). The scatter in the data between 80 and 120 cmbsf in the northwest corner of the test site is a result of a shelly layer with greater than 15% gravel.

Physical properties results from core sediments are also presented on Fig. 3 and indicate that the values change within the upper 25 cm as expected (e.g., wet bulk density increases, porosity decreases). All sediments contain between 88 and 95% $CaCO3$. Mean grain size increases at approximately 80 cm which is the average depth of a distinct shell layer.

Mineralogy

Sediments from both box cores and gravity cores were separated into gravel, sand, silt and clay particles, and the mineralogy of each fraction was studied using X-ray powder diffraction (XRD) and the subsequent Rietveld crystal structure refinement (Rietveld, 1969; Young et al., 1994). It was expected that the effect of chemical alteration to mineralogy would be greater in the fine grained fraction than the silt and sand fractions because the surface area available for diagenetic alteration is proportionally greater for small grains than for large grains. The Rietveld method of

refinement is capable of quantifying the calcium carbonate phases with various Mg contents (Bish and Post 1993). Although the accuracy of absolute values determined by this method is still debated (Mansour et al., 1995), the relative quantities of aragonite, high-Mg calcite and low-Mg calcite determined by the Rietveld method can be compared between samples (Reid et al., 1993). The Rietveld method also provides the cell constants of high-Mg and low-Mg calcites from which Mg contents can be calculated using the existing correlation curve (Goldsmith and Graf, 1958).

The sediments are a mixture of aragonite, high-Mg calcite, low-Mg calcite, and a non-carbonate fraction that is dominated by quartz. Whereas the ratio of aragonite to total calcite remains nearly constant throughout the gravity core sampling depths, the ratio of high-Mg calcite to low-Mg calcite increases at depths in the clay fraction (Fig. 4).

Geochemistry

Pore water samples were obtained from box cores using a Jahnke-type pore water squeezer (Jahnke, 1988) and analyzed for intermediate inorganic sulfur species and total inorganic reduced sulfur species using iodometric titration (Grasshoff, 1983; Fonselius, 1983) within 10 minutes of the completion of sample. Major and minor cation concentrations were determined using inductively coupled plasma spectroscopy (ICP) by Dr. C. Holmes at USGS Denver office. The pore water samples were also analyzed for pH within 10 minutes of sampling.

A shift in [Ca^{2+}] or [Mg^{2+}] may indicate dissolution or precipitation of calcium carbonate phases. Such a shift was not observed in the upper 30 cm of sediment in the study area (Fig. 5). However, because of the reworking due to bioturbation suggested by the presence of organisms and storm mixing suggested by the very shelly layers, the lateral mixing of porewater must be extensive in the study area. Therefore, [Ca^{2+}] and [Mg^{2+}] cannot be used as indicators of the extent of seafloor diagenesis, at least within the upper 30 cm of sediment.

Microfabric

Microfabric was studied at several scales utilizing thin sections, scanning and transmission electron microscopy. Thin sections revealed the complex nature of the Dry Tortugas sediments but were not appropriate for image analysis (Fig. 6).

Scanning electron imaging revealed the microfabric of the Dry Tortugas sediment to be composed of large numbers of halimeda plates, foraminifers, pelecypod fragments, bryozoans, framboids, and numerous other fragments, most unidentified. Because the field of view is limited to a few hundred microns at most, large shells and other material can not be imaged using this technique. (Fig. 7)

Measured bulk porosity of these sediments is ~61% decreasing to ~48% over 180 cm. Image analysis porosity from SEM micrographs (Lavoie et al, 1996) is much lower than the bulk porosity. This discrepancy is apparently because the image analysis measures primarily interparticle porosity at the SEM scale. It is evident at the TEM scale (Fig. 8) that much of the

bulk porosity is contained within the grains, in this case the Halimeda plates. Additional porosity is probably contained around shells too large to be sampled for fabric study.

SEM microscopy was also used to study cement formation. The SEM images of the silt fraction, for example, show that grains are coated with cryptocrystalline clumps at depths that may be the products of precipitation (Fig. 9).

The value of our microfabric study is not so much to predict bulk properties such as porosity, but to characterize the sediments in terms of the the distribution of porosity, type and location of cementation and other alteration fabrics, and constituent particles.

CONCLUSIONS

Key West Campaign

° In situ values of shear modulus and shear wave velocity agree well with predicted values using Bryan and Stoll's model (1988). Laboratory-measured values are significantly different and indicate the need to measure shear wave velocity under the appropriate effective stress conditions.

° Key West sediments are very complex; physical properties values show significant lateral and vertical variability, and is controlled by grain size and the distribution of numerous shells.

° X-ray diffraction, supported by SEM evidence, suggests that significant alteration is occurring within the smallest grain size fractions

° Pore water chemistry in the upper 30 cm suggests that considerable sediment mixing has occurred, probably by bioturbation and/or storms.

° Image analysis estimates of porosity for these shallow-water carbonate sediments requires consideration of both inter- and intraparticle porosity. Interparticle porosity accounts for only half the total measured bulk porosity. The remaining porosity probably resides within particles such as *Halimeda* plates and around shells too large to be imaged.

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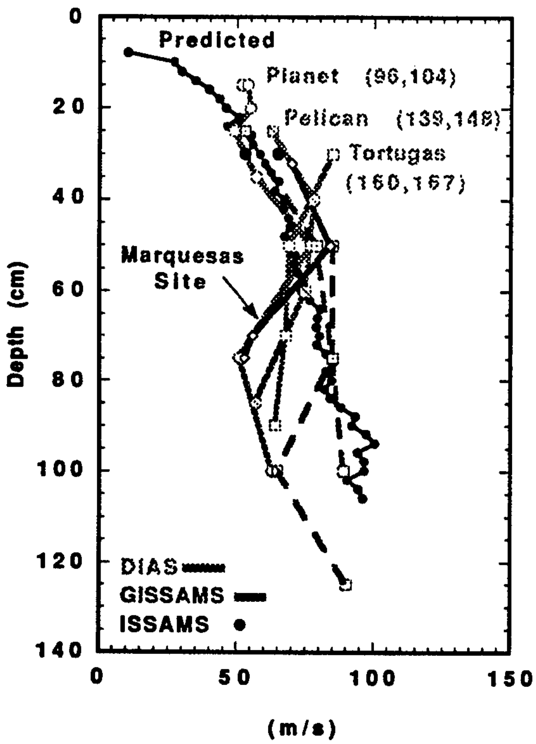


Figure 1. In situ shear wave velocity measured using the DIAS and ISSAMS systems agree well with the predicted values to ~75 or 80 cm bsf. Divergence between measured and predicted values may be caused by scattering off the dense shell layer at that depth. Below 100 cm where the shell size and density decrease, measured and predicted values of shear wave velocity begin to converge.

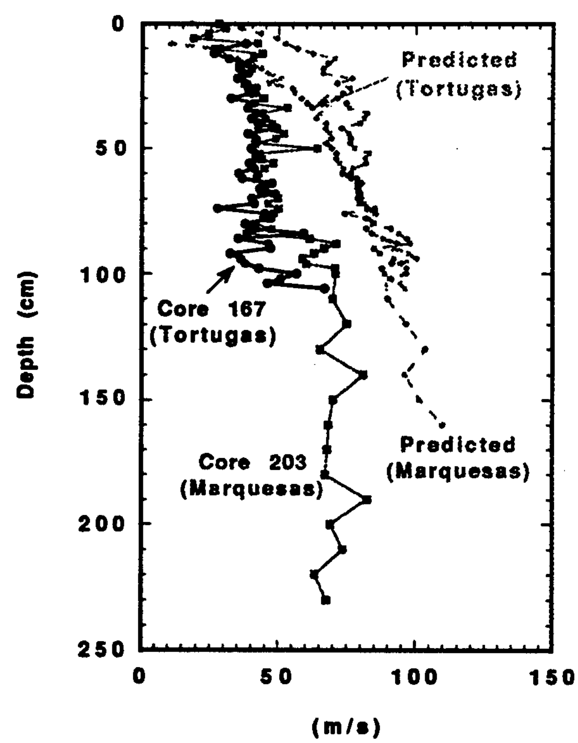


Figure 2. Shear wave velocity measured on cores using the Hamilton frame with shear wave transducers at ambient laboratory pressures is lower than either predicted values (Bryan and Stoll, 1988) in situ measured values. This suggests that shear wave velocity should be measured at in situ pressures to achieve valid data.

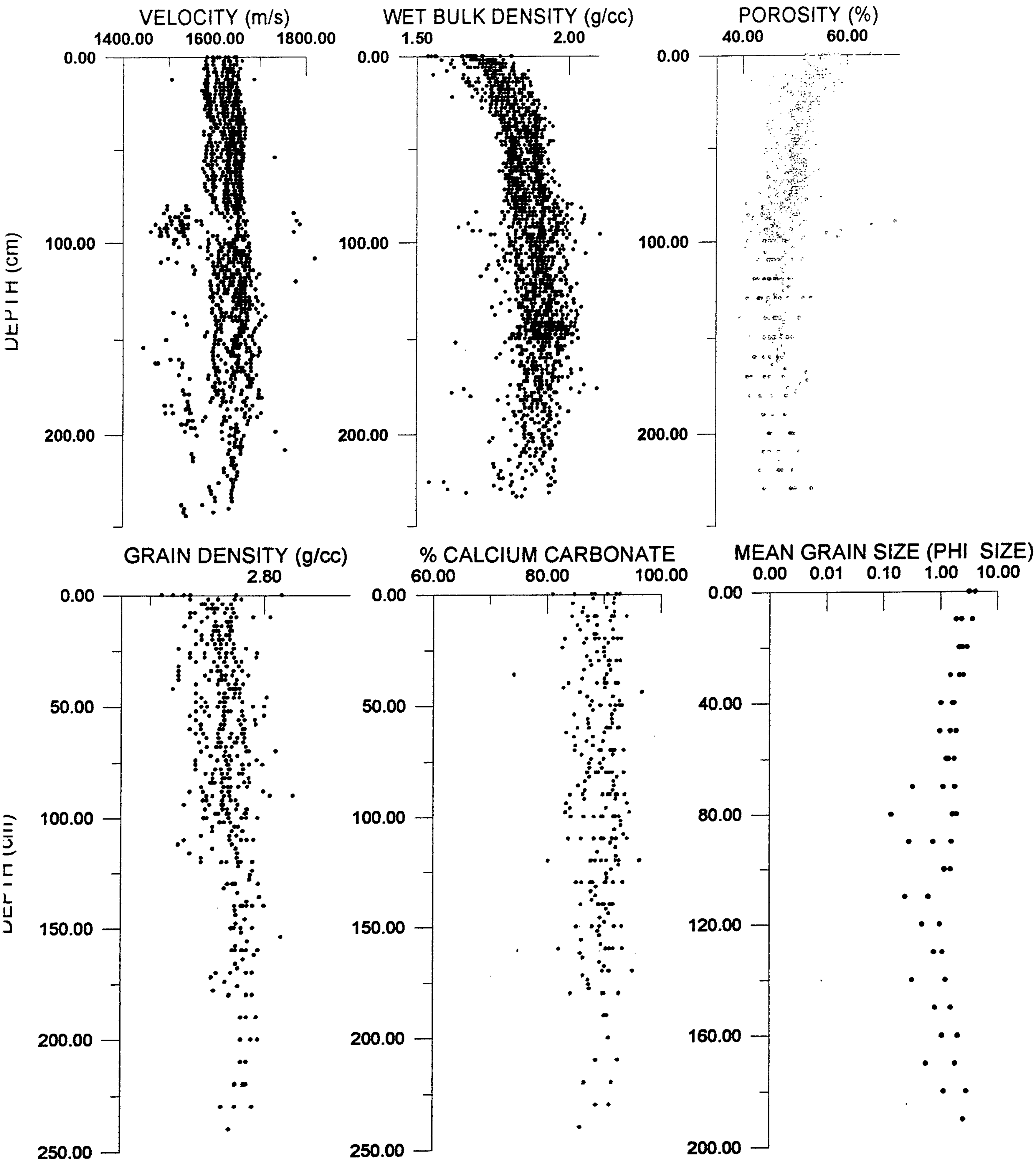


Figure 3. Compressional wave velocity and wet bulk density were measured using TAMU's core logger; porosity and grain density using NRL's pycnometer; calcium carbonate using a carbonate "bomb"; and grain size according to Folk (1974).

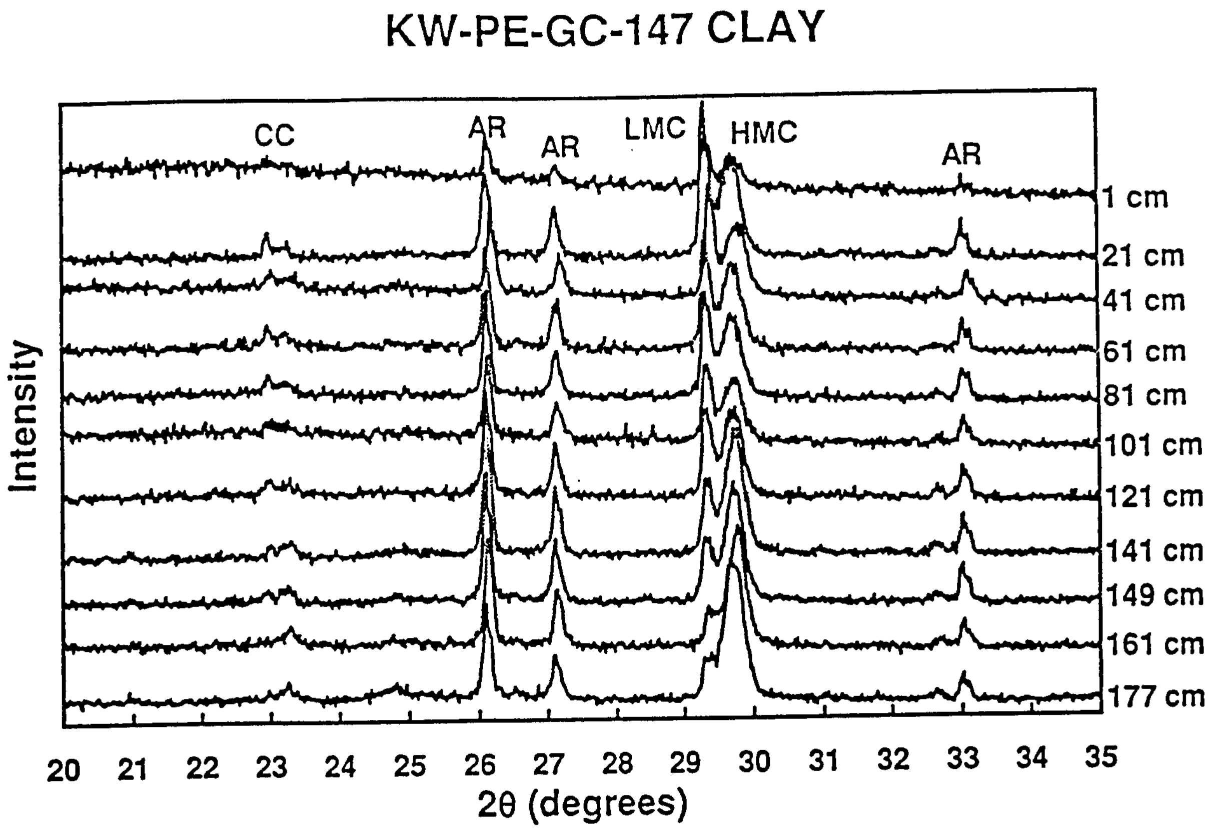


Figure 4. Example X-ray diffractogram illustrating the increase in high-Mg calcite with increasing depth down core. (CC, calcite; AR. aragonite; LMC, low-Mg calcite; HMC, high-Mg calcite)

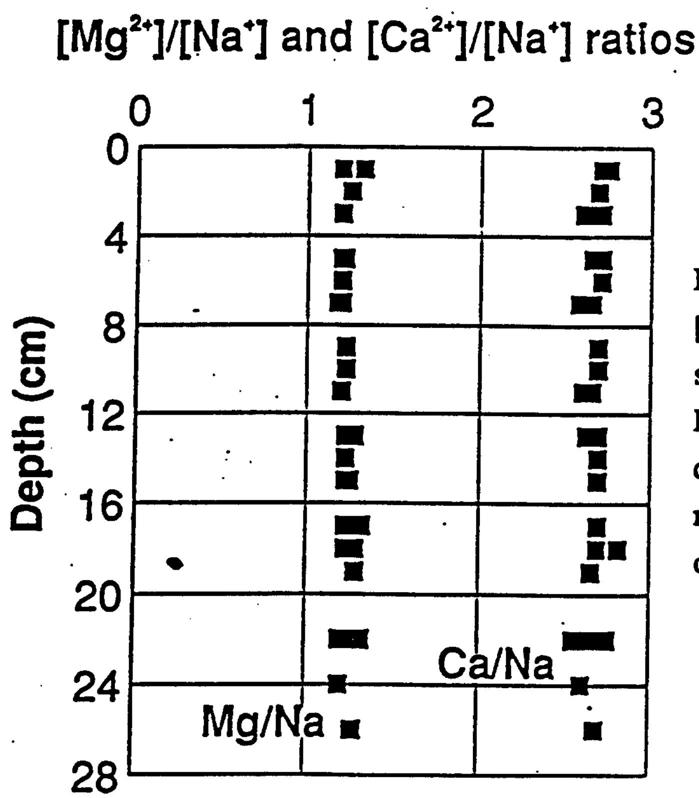
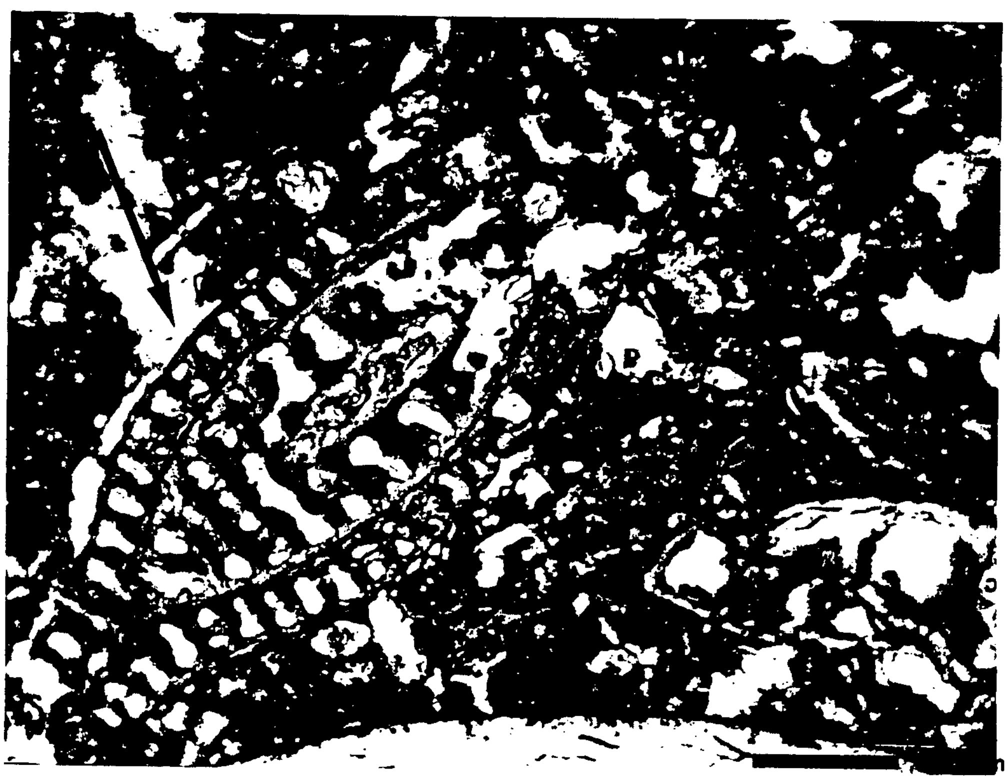


Figure 5. $[Mg^{2+}] / [Na^+]$ and $[Ca^{2+}] / [Na^+]$ ratios measured on samples from three box cores (KW-PL-BC-141, 165 and 194) and from a diver core (KW-PL-DC-179). The ratios remain nearly constant throughout the sampling depths.

KW-PE-GC-147 (36-37) cm bsf :*Miliolid*, bivalve fragment



KW-PE-GC-147 (168-170) cm bsf :*Archaias*

Figure 6. Thin section photographs showing typical constituents of sediments from the Dry Tortugas test site.

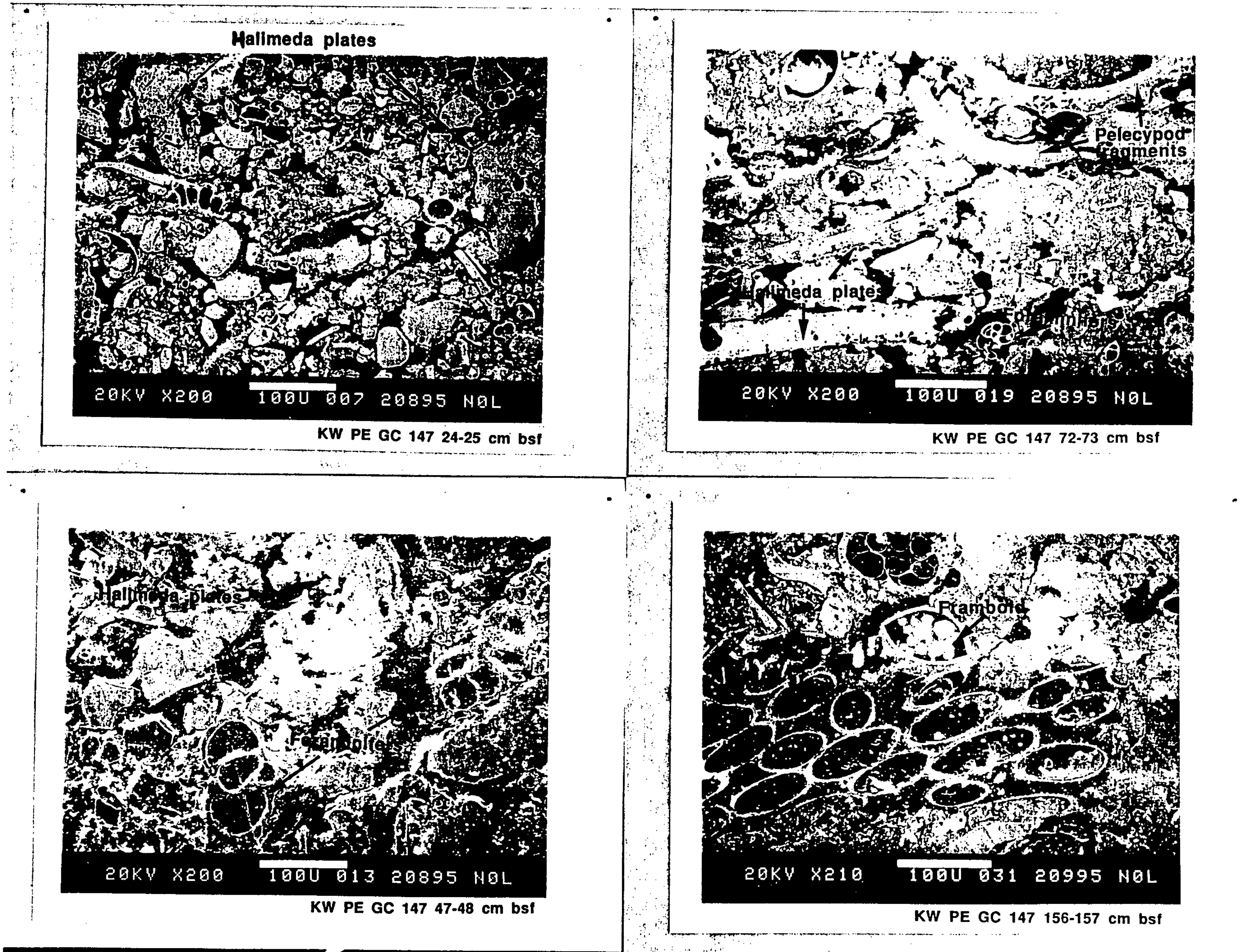


Figure 7. SEM micrographs illustrating typical weathered Halimeda plates.

Figure 8. TEM micrographs of (a) Halimeda plates nestled within the very fine-grained matrix and (b) TEM micrographs of the aragonite needles within the Halimeda plate. (b) illustrates the high porosity found within the grains.

KW-PE-GC-147
121 cmbsf

KW-PE-GC-147
21 cmbsf

KW-PE-GC-147
1 cmbsf

Figure 9. SEM micrographs illustrating the overgrowths found on silt-sized grains from the Dry Tortugas.

2.11 Quantification of Biogeochemical Processes Controlling Early Diagenesis and Biogenic Gases in Marine Sediments (Principal Investigators: C.S. Martens and D.B. Albert)

CBBLSRP FY95 YEAR-END REPORT

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INTRODUCTION

The scientific priorities of the Coastal Benthic Boundary Layer Special Research Program (CBBLSRP) include determining the effects of biogeochemical processes on coastal sediment properties and structure. During the first three years of the program, emphasis has been placed on studies of the gassy sediments of Eckernfoerde Bay. In collaboration with other investigators we have focused our research efforts on the quantitative studies of biogeochemical processes which control production, consumption and transport of biogenic methane at this site. We have also conducted parallel investigations in nearby gasy sediiments accessible for directly related studies of seasonal variability in key processes and participated in CBBLSRP experiments off Panama City and in the Florida Keys.

Our primary goals include quantification of the mechanisms and rates of microbially-mediated reactions associated with organic matter degradation and the development of predictive models for the occurrence of these processes in a variety of sedimentary environments

OVERVIEW OF PROGRESS THROUGH SEPTEMBER, 1995

Our work during the past year has focused on biogeochemical processes controlling dissolved gases and gas bubbles in organic-rich sediments from two sites chosen for intensive work by the CBB>SRP team. These are the gassy sediments of Eckernfoerde Bay and carbonate-rich sediments near the Dry Tortugas in the Florida Keys. In addition we have concucted a series of related studies at local site including Cape Lookout Bight and the White Oak River Estuary in North Carolina. The work has included studies of:

i) concentration distributions of dissolved oxidants and biogenic gases

ii) depth variations in the light stable isotopic composition of biogenic gases

iii) depth variations in the solid phase concentrations of organic carbon, total nitrogen and total reduced sulfur

iv) depth variations in the $\partial^{13}C$ and $\partial^{15}N$ values of solid phase organic carbon and total nitrogen

v) rates of microbially-mediated reactions including sulfate reduction, methane production and methane oxidation

vi) chemical mass balances for the elements C, N and S including remineralization and burial fluxes

vii) kinetic models of aqueous phase individual downcore concentration and isotopic distributions as well as solid phase C, N and S distributions

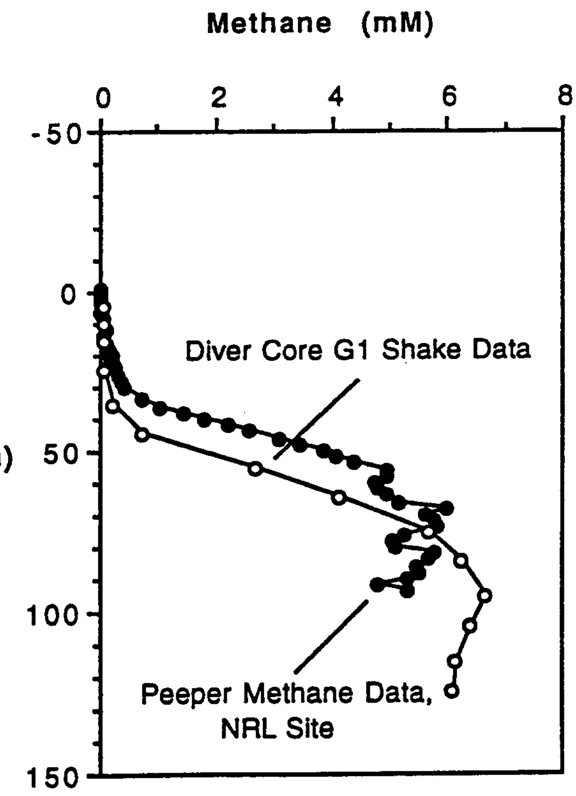
In the following paragraphs, work completed in each of these subject areas is briefly reviewed. Additional information, including illustrations, is available if desired.

Concentration distributions

Work on biogenic gas concentration distributions has included comparisons of data from membrane equilibration samplers (peepers) and whole sediment extraction methods at Eckernfoerde and other sites. A comparison of peeper and whole sediment data from the NRL site is shown in Figure 1. The data agree very well indicating that both shipboard methods provided accurate data free from substantial degassing artifacts.

We have also attempted to obtain concentration data from a chemical probe device modified to fit on M. Richardson's Big ISSAMS platform during the Florida Keys expedition. We were able to attach the probe as planned and perform on-deck tests; however, the platform's pump system was not functional and no field deployments were made.

Figure 1

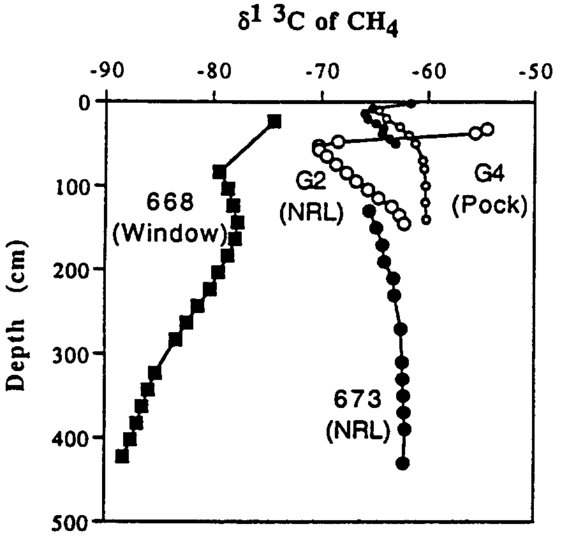


Depth variations in isotopic composition

Light stable isotopic measurements of methane and total dissolved inorganic carbon were made during the 1994 Eckernfoerde expedition at three different sites: NRL, acoustic window (window) and pockmark (pock). Comparisons of $\partial^{13}C$ values of the methane at

the three sites are illustrated in Figure 2. A primary difference is the generally lighter $\partial^{13}C$ values for the window site where the influence of groundwater moving through the carbonate-rich till layer is clearly seen. The same oxidation effect leading to heavier $\partial^{13}C$ values in the upper 50 cm of the sediment column is seen at all three sites.

Emphasis was placed on obtaining detailed isotopic data for methane and ΣCO_2 from theNRL site and both stable C and H isotopes were run on the methane. Results from one core are shown in Figure 3. Both $\partial^{13}C$ and ∂D isotopic values become heavier in the upper 50 cm proving the importance of anaerobic methane oxidation in maintaining low concentrations up the the sediment-water interface. The constant ∂D values at depth indicate lack of oxidation below the sulfate reduction zone while increasingly heaavy $\partial^{13}C$ values reflect the heavier $\partial^{13}C$ of the ΣCO_2 being reduced to methane (Figure 4).



3 Site Methane Isotope Comparison

Figure 2

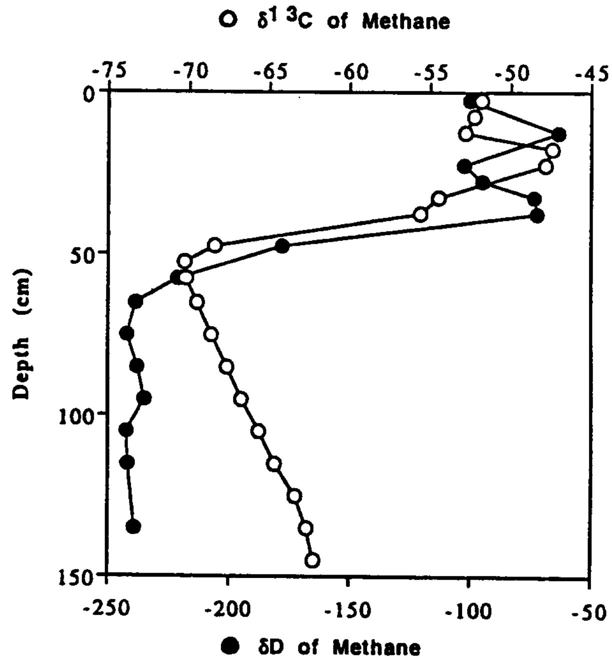


Figure 3

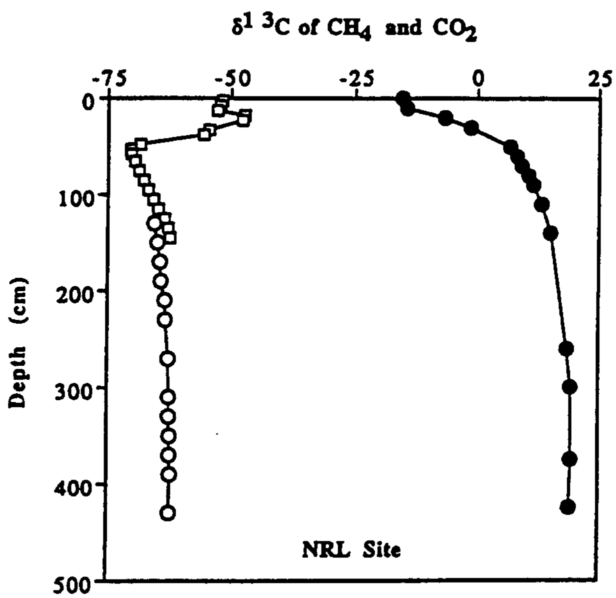


Figure 4

Solid phase elemental C,N,S and $\partial^{13}C$ and $\partial^{15}N$ analyses

We have evolved state-of-the-art capability to conduct dual $\partial^{13}C$ and $\partial^{15}N$ measurements on solid phase sediment samples. This has been made possible through combining an elemental CNS analyzer with our MAT 252 mass spectrometer through a combustion interface. At this moment our system appears to be the most advanced in the world in achieving this dual measurement; however, we are working with the Finnegan MAT Corporation to correct "bugs" in their software and to make necessary modifications to hardwarre in the interface. We are achieveing excellent $\partial^{13}C$ results but want somewhat better $\partial^{15}N$ precision before running all of the samaples from Eckernfoerde, the Dry Tortugas and other sites. All samples have been ground and should be run in the next few months, before the third year of our project is over. We should be able to make detailed comparisons of organic matter sources at all of our sites using the expected combined isotope results.

The solid phase elemental data are needed for the mass balance modeling discussed below.

Rates of microbially-mediated reactions

We have completed analysis of sulfate reduction rate (SRR) and methane oxidation rate (MOR) measurements from Eckernfoerde Bay and are working up sulfate reduction rate and sulfide oxidation rate data from the Dry Tortugas. Preliminary plots of SRR and MOR versus depth at Eckernfoerde appear in Figures 5 and 6 respectively.

The SRR results agree with the methane stable isotopic results discussed above in that a subsurface peak coincides with the inferred depth of maximum methane oxidation at 20-30 cm. These results, in turn, agree with directly measured MOR results (Fig. 6).

It is important to recognize that the stable isotopic data are best utilized as an indication of controlling mechanisms whereas the direct rate measurements are required to quantifay the processes. It is the combination of concentration, stable isotope and rate measurements which makes our work in Eckernfoerde unique. The combination of data should also allow for new and improved models of these processes.

Figure 5

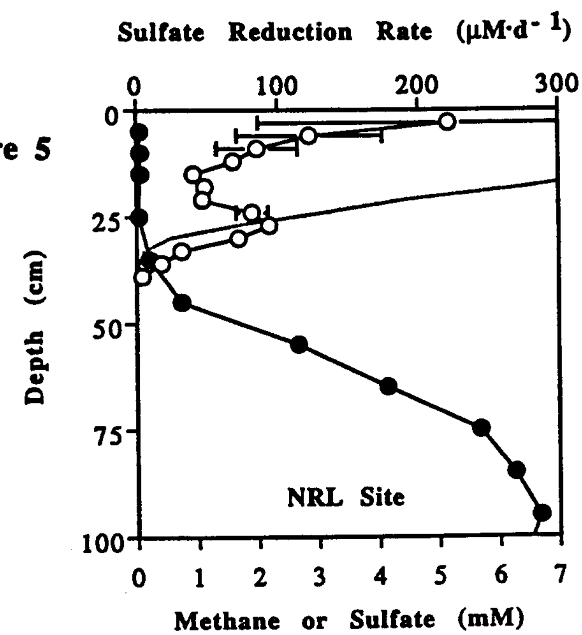
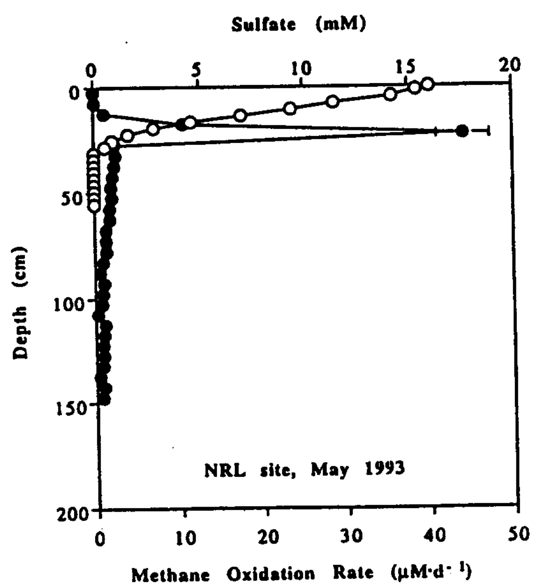


Figure 6



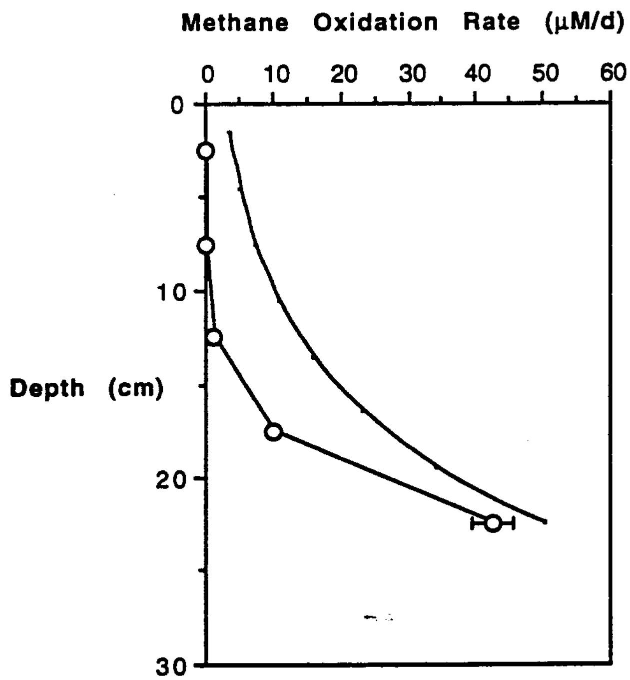
Chemical mass balance for C,N and S

Measured rates of sulfate reduction by our group and sediment burial rates calculated from solid phase elemental analyses plus ^{210}Pb sediment accumulation rates from other researchers are being combined to produce sedimentary budgets for the elements C, N and S.

Kinetic models

We have utilized kinetic models to predict and quantify oxidation rates controlling the concentration distribution of methane in the upper meter of gassy sediments. Rates predicted for the Eckernfoerde NRL site are illustrated in Figure 7. The modeled rates can be compared with the measured rates shown in Figure 6 above. It has been demonstrated in our laboratory (Hoehler et al., 1994) that anaerobic methane oxidation is carried out by methane producers when molecular hydrogen concentrations are maintained at low values by sulfate reducers.

Figure 7



Papers Presented (1995)

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Martens, C.S. and D.B. Albert. Biogeochemical processes controlling concentrations and transport of biogenic methane in organic-rich coastal sediments. In: T. Wever (ed.) Proc. Workshop Modeling Methane-Rich Sediments of Eckernfoerde Bay. Eckernfoerde Germany 26-30 June, 1995.

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2.12 Physical and Biological Mechanisms Influencing the Development and Evolution of Sedimentary Structure (Principal Investigators: C.A. Nittrouer and G. R. Lopez)

CBBLSRP FY 95 YEAR-END REPORT

Physical and Biological Mechanisms Influencing the Development and Evolution of Sedimentary Structure

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Introduction

Research work during 1995 included completion of Eckernfoerde analyses and collection of data/samples in the Dry Tortugas/Marquesas study area. The results of Eckernfoerde studies were presented at the CBBL workshop during summer 1995 and in two preliminary papers as part of the *Geo-Marine Letters* special volume. Preparations of two final research papers and an integrated summary paper of Eckernfoerde work were started. These include modeling of strata formation, which is highlighted in this annual report. We participated in two research cruises to the Dry Tortugas and Marquesas, and collected over 200 cores in coordination with boundary-layer and acoustic observations. These data will help us to contrast strata formation in a carbonate setting with that observed in siliciclastic settings. Analyses of these new samples started in 1995, as described below.

Results and Conclusions Regarding Modeling in Eckernfoerde Bay

Previous studies have proposed that the subtle laminations in the silty-clay sediment of Eckernfoerde Bay are a function of alternating storm and fair-weather sediment transport and accumulation (Milkert, 1994; Friedrichs and Wright, 1995), overprinted by shallow bioturbation (Bentley et al., 1996). In order to assess quantitatively the relationship between pulsed sediment deposition and rate of bioturbation, we examined laminations in thin section for evidence of progressive bioturbation with age, and compared these results with calculated values of disruption using the transit time/dissipation time model of Wheatcroft (1990). This model, derived from Crank (1975), addresses the diffusional modification of an event layer (of some initial concentration C) undergoing bioturbation during transit through the mixed layer, as follows:

$$C = 0.5\, C_0\, erf\,[L_s/(2(D_b T_m)^{1/2}]$$

where C_0 is initial tracer concentration in the event layer, *erf* is the error function (a tabulated mathematical function), L_s is the event-layer thickness (cm), and D_b is the biodiffusion coefficient. T_m is the event-layer transit time through the mixed layer, given in simplest form by L_b/w, where L_b is the mixed-layer thickness (cm) and w is the accumulation rate (cm/yr). Excess ^{234}Th activities permitted estimates of D_b (~ 0.7 cm^2 yr^{-1}) in central basin sediments, using a solution to the steady-state advection/diffusion equation (Aller and Cochran, 1976).

For application of the model, we considered percent pelletization of sediment to approximate the extent of bioturbation undergone by an event layer. Reingestion and microbial decay of fecal pellets are assumed to have negligible effect on pellet concentration. Oxic water-column conditions are assumed as well, allowing rapid recolonization of the substrate surface. Table 1 compares modeled and observed layers of pelletization in a storm layer 10 mm thick.

Model results can be interpreted as either progressive bioturbation of a single storm layer through time, or as measurements of bioturbation under fluctuating accumulation rates (as indicated by varying transit times: recall that $T_m = L_b/w$). Computed results indicate that fluctuations in sediment input will influence the degree of bioturbation and thus of pelletization, both at high depositional rates, represented by the short transit times in the 5-7 mm depth range, and at intermediate rates (longer transit times, 2-4 mm depths).

Although degree of pelletization increases upward from the basal contact in both modeled and measured results, modeled values of percent pelletized sediment are higher at depth than those determined for corresponding locations in thin sections. The true measure of bioturbation intensity in these sediments probably exists between model results on the high end, and percent pelletized sediment on the low. Three observations support this assertion. First, observed fecal pellets represent only the contribution of tellinid bivalves and capitellid polychaetes to sediment modification, and do not incorporate bioturbation by other members of the benthic community. Thus, observed degree of sediment pelletization should be a minimum measurement of bioturbation, whereas model results integrate the activities of all organisms mixing the sediment at our scales of observation. Second, the model assumes steady-state biodiffusion, which is not likely when $L_b \leq L_s$; under these conditions, a lag in bioturbation rate not incorporated into the model should occur during the early stages of recolonization (Jumars and Wheatcroft, 1989). Third, organism patchiness and depositional surface irregularities introduce non-uniform gradients into natural microfabric, thus introducing error in correlations of modeled and observed values.

The aim of the biological component in Eckernfoerde Bay was to characterize the role of the benthic community in vertical particle mixing and sediment transport. Functional-group analysis was used to determine the successional status of the benthic community and the potential role in vertical mixing, defined here as the vertical displacement between feeding and defecation, of the functional groups present in this system: surface deposit feeders, head-down deposit feeders, carnivores/scavengers, and suspension feeders. The benthic community of Eckernfoerde Bay was dominated by opportunistic surface deposit feeders, particularly the spionid polychaete *Polydora ciliata* and the tellinid bivalve *Abra alba*. Head-down deposit feeders such as capitellid polychaetes were the next most abundant group. Bioturbation experiments and radiochemical analysis indicate that this community mixed the top 0.5-1.0 cm of the sediment on rapid time scales (< 14 days)(D'Andrea et al., 1996; Bentley et al., 1996). Particle bioturbation is best incorporated into models as a biological mixing or "biodiffusion" coefficient (Berner 1980; Aller 1980; Guinasso and Schink 1975; Goldberg and Koide 1962). The biodiffusion coefficient estimated in particle mixing studies can be decomposed into the following form: $D_b = \delta^2/2\Omega$, where D_b represents the biodiffusion coefficient, δ the mean step length, and Ω the mean rest period (Wheatcroft 1990). Our results indicate that the vertical

displacement between ingestion and defecation of particles is important in determining the step-length portion (δ) of the biodiffusion coefficient, and is directly related to the functional group (Table 2). In Eckernfoerde Bay, the step length is controlled primarily by head-down deposit feeders such as capitellid polychaetes, despite the numerical dominance of surface deposit feeders. The benthic community is maintained at a low level of complexity due to a regular disturbance, most likely seasonal hypoxia/anoxia.

The sizes and abundances of deposit feeders and the fecal pellets they produce were used to determine whether the fecal pellet sizes and abundances were capable of being produced by the resident population in the central basin. Deposit-feeder fecal pellets are typically aggregates of finer particles, and can be fairly robust to decomposition and breakage. They are then subject to benthic-boundary-layer processes such as bottom stress, resuspension and transport. We concentrated on determining if the spatial distribution of fecal pellets was a good indicator of sedimentary processes occurring in Eckernfoerde Bay. The primary fecal pellet producers identified for this system were the tellinid bivalve *Abra alba*, capitellid polychaetes, and tubificid oligochaetes. Fecal pellet abundance increases almost exponentially with water depth; the greatest abundances were found in the central basin (Fig. 1). Pellet size is significantly greater in the central basin than along the shallower flanks of the bay (Fig. 2). The largest fecal pellet producers, however, were found at the shallowest stations where the smallest pellets and lowest abundances of fecal pellets were found (Fig. 1). Our results indicate that there is a winnowing of robust fecal pellets from the steep slopes along the flanks of Eckernfoerde Bay into the central basin. The abundance of fecal pellets follows the pattern of sediment transport and deposition in Eckernfoerde Bay and supports the hypothesis that the central basin is a sink for fine particles. Our results indicate that the spatial distribution of robust fecal pellets may be a good biogenic indicator of sedimentary processes in some shallow coastal systems.

Description of Preliminary Work in Marquesas/Tortugas

Sedimentological studies were undertaken in the Dry Tortugas and Marquesas islands to elucidate the relationship between physical and biological processes in the benthic boundary layer and resultant preserved sedimentary fabric in a carbonate-shelf setting. More specifically, our sampling program was geared toward three goals: studying temporal and small-scale spatial variability (biological and sedimentological) of the seabed in the vicinity of the VIMS tetrapod during the period of its deployment in the Dry Tortugas; characterizing temporal and spatial seabed variability of the Tortugas study site as a whole (~ 30 km^2), and to a lesser extent, the Marquesas study site (~ 70 km^2); and establishing a regional framework of benthic-community and sedimentary-fabric distributions over areas south and east of the Tortugas (~ 500 km^2) and north and west of the Marquesas (~ 100 km^2). To achieve these goals, 210 box cores and 14 gravity cores were recovered.

Cores are being examined by observations of x-radiographs, microfabric (using image analysis techniques), grain size, and ^{234}Th, and ^{210}Pb geochronology. Using the results from these analyses, we plan to evaluate quantitative models of strata formation, such as the Wheatcroft model (1990), discussed above, for applicability to fine-grained carbonate-shelf depositional environments.

Initial results indicate that both the Marquesas and Tortugas study sites are subjected to interacting biological and physical sediment transport and mixing mechanisms. Radiographs of both sites display a thin (2-5 cm) layer of high-porosity sediment blanketing a very shelly, more-consolidated carbonate mud. Cross-stratification is frequently observed in the surface layer of radiographs of Marquesas cores. In contrast, the surface layer of cores from the Tortugas is frequently homogenized by bioturbation. Deeper sediments from both sites are generally intensely bioturbated, containing large vertical burrows (to 1 cm inside diameter, probably produced by Callianassid crustaceans; Tedesco and Aller, in press), deposit-feeding traces (horizontal-meniscate backfilling, characteristic of heart-urchins; Bromley, 1990) as well as numerous small (< 0.5 cm) vertical and inclined burrows (produced by unidentified vermiform organisms). Only rarely are vestiges of primary depositional structure evident.

Excess ^{234}Th was limited to the upper 2 cm of two cores recovered near the VIMS tetrapod. This depth corresponds to the thickness of fluffy surface layer, seen in radiographs taken from the same cores (Fig. 3), and indicates that this layer is probably well-mixed on time scales approaching the half-life of ^{234}Th (Aller and Cochran, 1976). An algal mat blanketed the sediment surface over much of the study area, probably inhibiting sediment remobilization (physical mixing) by all but the most energetic events (ripples were observed to form on disturbed, unmatted sediment, following the passage of a storm in late February 1995). Bioturbation and physical mixing both appear to be important in the surface layer of the Dry Tortugas site.

Although measurable excess ^{234}Th appears to be restricted to a relatively thin surface sediment layer, bioturbation is significant below the surface layer, judging by the well-developed biogenic fabric described above. Vertical zoning of specific biogenic structures is typical of a tiered ichnofabric, and should closely relate to benthic community structure and rates and episodicity of sediment accumulation (Bromley and Ekdale, 1986; Boudreau, 1994; Tedesco and Aller, in press).

Biological samples were concentrated around the tetrapod deployment site in the Dry Tortugas study site, but included samples throughout the grid and near Marquesas to get a regional perspective. Overall, benthic samples were taken from 119 box cores. These included 40 box cores from the tetrapod site, 42 from the Dry Tortugas study area, and 37 box cores from the Marquesas and regional stations. Preliminary work on the samples indicate three organisms with the greatest bioturbation potential: Callianassid shrimp, capitellid polychaetes, and sipunculan worms. Callianassid shrimp are commonly selective deposit feeders which live in deep burrow systems. These burrow systems typically include galleries where coarser sediment and fecal pellets are stored. These galleries could affect this system by creating large void spaces in the sediment and biologically graded bedding. The capitellids found in this system (dominated by *Notomastus*) are rather large (up to 10 cm long). This group of polychaetes are head-down deposit feeders that feed at depth and defecate at the surface. Sipunculan worms are active burrowers, although some live in mucus-lined burrows, and are mostly nonselective deposit feeders. These three species should be the dominant bioturbators of this system. Future work will focus on relationships between sediment accumulation rates, benthic community structure, hydrodynamic conditions, and sedimentary structures.

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Table 1. Model results: degree of pelletization of a storm layer with resumed accumulation and bioturbation. $C_0 = 100$, $D_b = 0.7\ cm^2\ yr^{-1}$, $w = 7\ mm\ yr^{-1}$.

Initial depth (mm) from surface	Transit time to historical layer (yr)	% Pelletized sediment in historical layer, modeled results	% Pelletized sediment estimated from BS4-602, 6.4-7.1 cm depth
1	1	71	70
2	0.86	69	60
3	0.71	67	40
4	0.57	64	30
5	0.43	60	20
6	0.29	56	15
7	0.14	51	10 (basal contact)

SURFACE DEPOSIT FEEDERS	(SDF)	Vertical Displacement (δ)
Polydora ciliata	polychaete	~0 cm
Abra alba	bivalve	~0 cm
Diastylus rathkei	crustacean	~0 cm
HEAD-DOWN DEPOSIT FEEDERS	(HDF)	
Capitella sp.	polychaete	~1 cm
Heteromastus filiformis	polychaete	~1 cm
tubificid sp.	oligochaete	~1 cm
Pectinaria koreni	polychaete	2-3 cm
Scoloplos armiger	polychaete	2-3 cm
CARNIVORES/SCAVENGERS	(C)	
Anaitides maculata	polychaete	~0 cm to 1cm (burrowing)
syllid sp.	polychaete	~0 cm to 1cm (burrowing)
Nepthys sp.	polychaete	~0 cm to 1cm (burrowing)
Hermathoe sp.	polychaete	~0 cm to 1cm (burrowing)
Sigambra sp.	polychaete	~0 cm to 1cm (burrowing)
SUSPENSION FEEDERS (SF)		
Mytilus edulis	bivalve	~0 cm
Cerastoderma sp.	bivalve	~0 cm
Corbula gibba	bivalve	~0 cm

Table 2. Rank order of dominant macrofauna in Eckernfoerde Bay and vertical displacement between feeding and defecation for individual species.

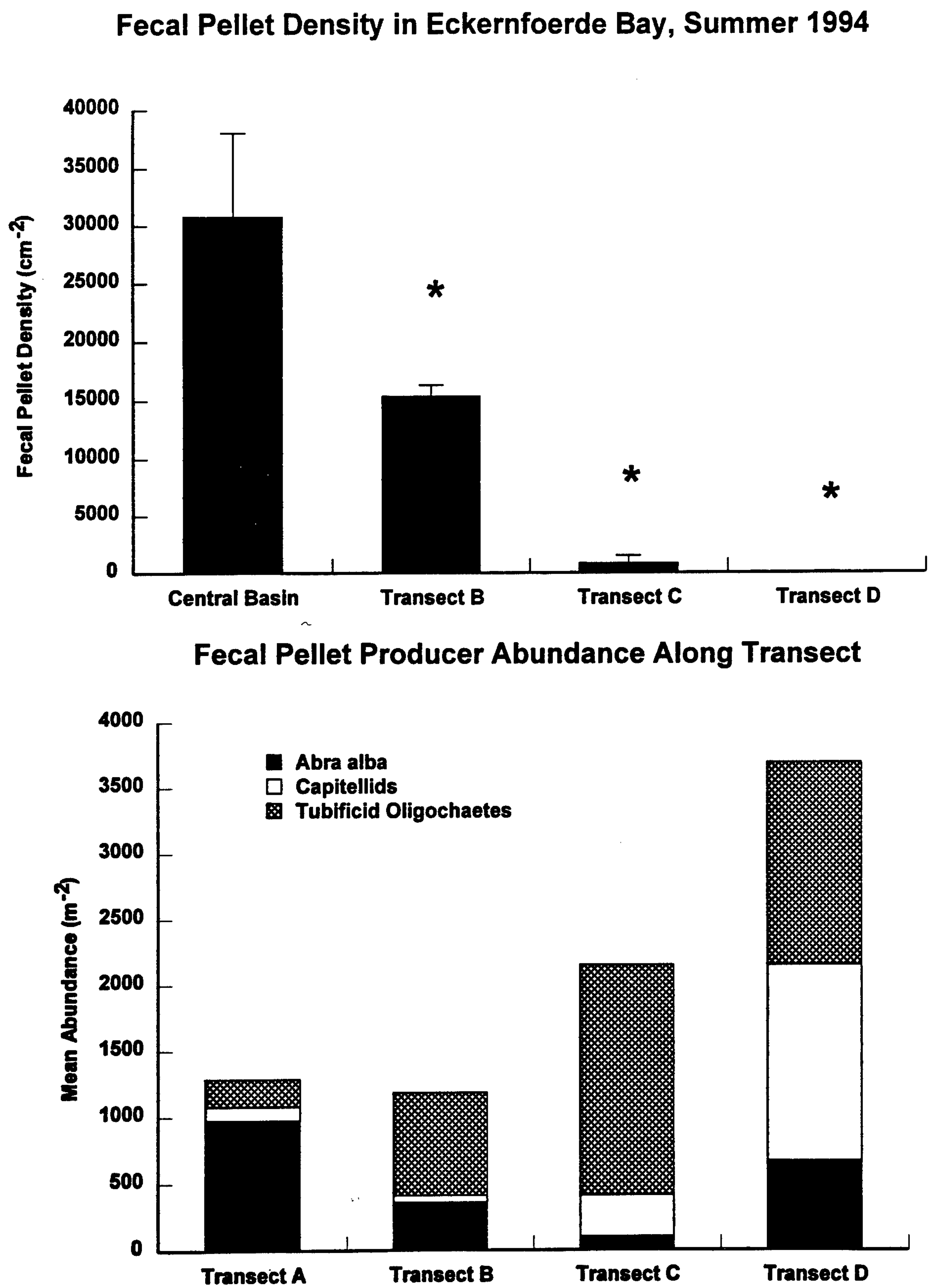

Figure 1. Fecal-pellet density (top) and fecal-pellet-producer abundance (bottom) from the central basin to the shallowest transect station (Transect D = 14m).

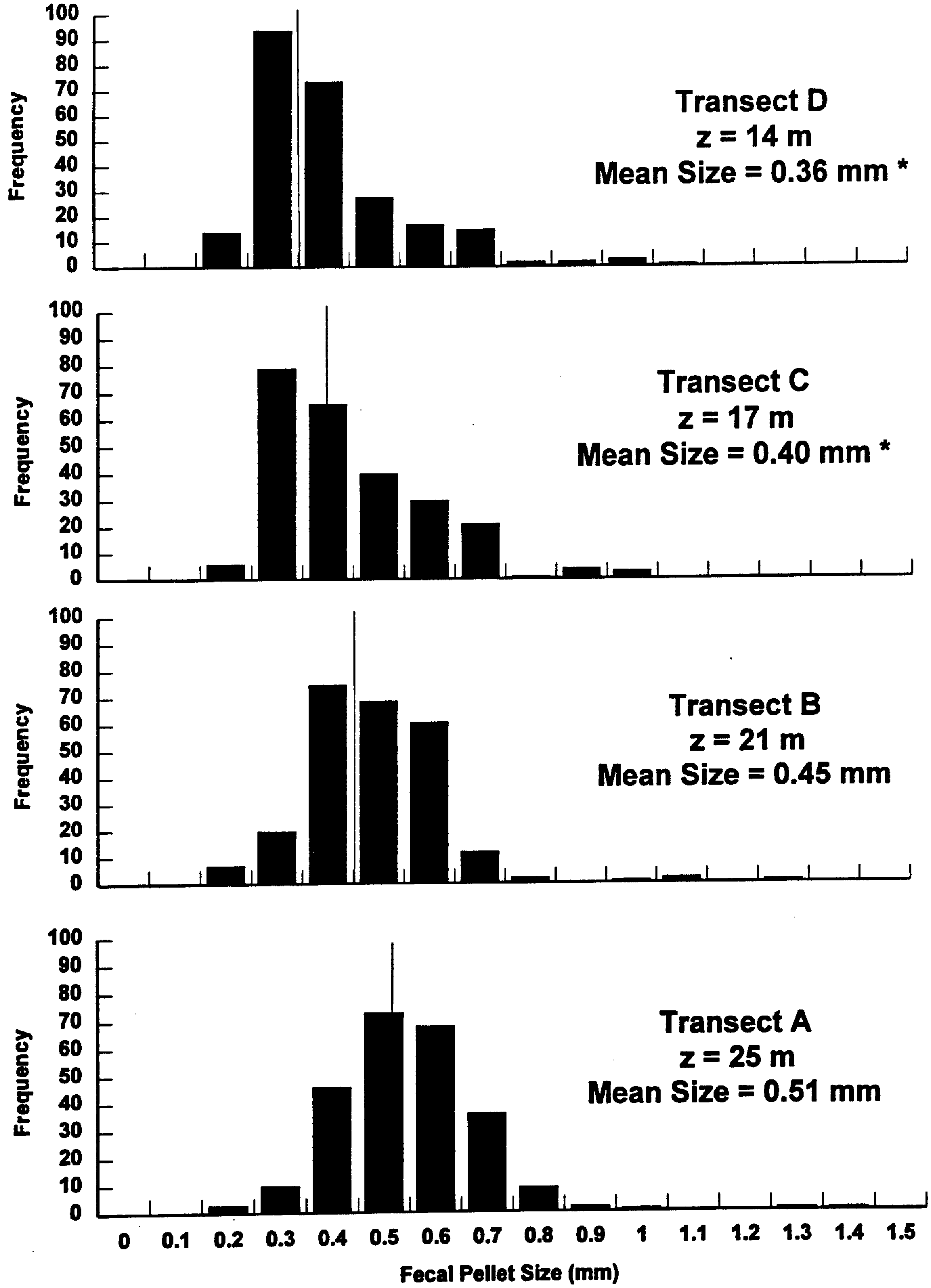

Figure 2. Size frequency of fecal pellets from the shallowest transect station (top) to the central basin (bottom). Mean pellet size is indicated by a single vertical line in each distribution. * = significantly lower mean length than the central basin (α = 0.05).

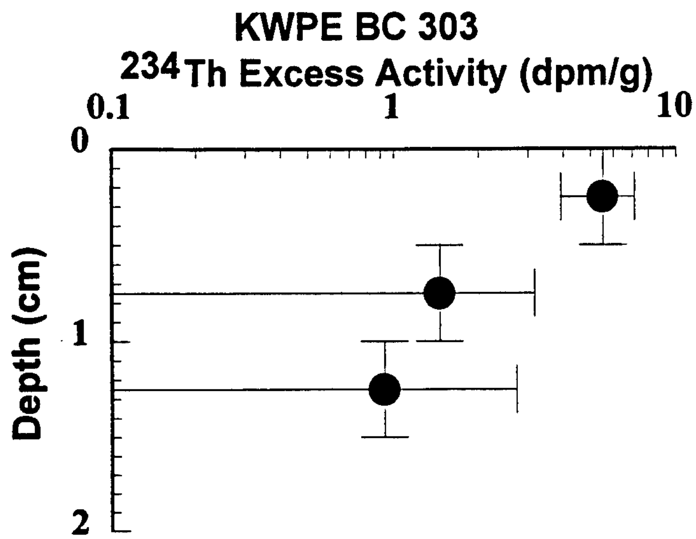

Figure 3. Excess ^{234}Th activity profile from KWPE BC-303. Note that the thickness of the layer containing excess ^{234}Th corresponds to the surface layer seen in x-radiographs.

2.13 Detection of Continuous Impedance Structures Using a Full Spectrum Sonar (Principal Investigator: S. Schock)

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Objectives:

1. To develop an acoustic model that predicts the frequency response of the seabed from vertical impedance profiles estimated from sediment cores

2. To utilize the acoustic model to develop a reflection profiling technique for measuring the vertical impedance profile of the top 10 meters of the seabed

3. To acquire normal incidence FM reflection data over the frequency range of 1 to 15 kHz for imaging the subsurface features of the seabed and for estimating sediment properties at CBBL experiment sites

4. To test algorithms for sediment property prediction developed for the Office of Naval Research and to compare those properties with in situ property measurements made by other CBBL investigators

1994-1995 Accomplishments:

1. The FAU research program developed a numerical model for predicting the impulse response of the seabed from vertical impedance profiles calculated from relative velocity and bulk density measurements on cored sediments. This model accounts for all interlayer interactions to provide an accurate estimate of the frequency response of the seabed. Important results from the model include:

a) Sediment cores should be sampled for velocity and bulk density at 0.5 cm intervals to accurately estimate the frequency response of the seabed up to 15 kHz with a maximum error of 1.5%.

b) When density gradients exist at the sediment-water interface, the reflection coefficients measured by subbottom profilers operating at different frequencies can differ by as much as 6 dB. The reflection coefficient needs to be measured over the frequency range of 500 to 15000 Hz to provide a reliable estimate of surficial sediment impedance

2. This research program collected normal incidence reflection data during the 1995 Key West cruise in February 1995 using a towed vehicle transmitting and receiving FM pulses with the following frequency bands: 1.5-7.5 kHz, 1-6 kHz, 0.5-3 kHz, 1-10 kHz, 1-12 kHz. Figure 1 shows the track lines for the acquisition of FM data. Table 1 lists a chronology of the survey including trackline numbers and pulse operating bands. Table 2 provides a list of sediment cores taken within 100 meters of the ship's track, the distance from the tow fish to the core site at the closest point of approach, and the predicted surficial impedance at the core site. Table 2b provides a comparison between the surficial impedance predicted from sonar data and the surficial impedance estimated from cored sediments which is the average value of the product of bulk density and compressional wave velocity measurements to a subfloor depth of one half acoustic wavelength. Tables 3, 4 and 4b provide the corresponding chirp sonar and core data comparisons for the Panama City cruise.

3. Investigations using the Biot-Stoll model demonstrated that estimating the surficial impedance from the reflection coefficient using the fluid-fluid model (Rayleigh reflection coefficient expression) will underestimate the surficial impedance of sand by as much as 10 %.

Tables 2b and 4b show that the surficial impedance predicted from the sonar data is consistently less than the impedance measured from sediment cores for the Panama City and Key West CBBL sites. For a seabed with a certain specific impedance, the measured reflection coefficient is less than that calculated using the expression the Rayleigh reflection coefficient because of energy conversion at the fluid-porous solid interface. This result is consistent with a numerical model of the fluid-porous solid interface. Figure 2 shows the reflection coefficient plotted against surficial impedance for the cases of the fluid-fluid and the fluid-porous solid boundaries. Using the Biot-Stoll model, one can numerically predict that when the measured reflection coefficient is above -14 dB, the surficial impedance predicted assuming a fluid-fluid interaction will be less than the actual impedance of the seabed. The chirp sonar measurements support this conclusion.

4. The FAU research program successively tested an inversion procedure for predicting vertical impedance profiles from normal incidence FM profiler data at core sites in Kiel Bay, Germany. A least squares inversion procedure that uses fuzzy logic to remove incoherent scatterers and a genetic algorithm to find the impedance profile with the minimum overall error was used to calculate the impedance profiles in Figures 3 and 4. The figures compare impedance profiles derived from sonar data and impedance profiles calculated by multiplying the velocity profiles and the bulk density profiles measured on cores. Near the sediment-water interface of both cores, the chirp sonar impedance measurements are less than the core-derived measurements; the discrepancy could be due to compaction of surficial sediment during the coring process which would increase sediment impedance. These comparisons show that the inversion procedure developed for the ONR sediment classification program looks very promising.

Conclusions:

This research has provided new knowledge in the area of normal incidence acoustic - sediment interactions and remote acoustic measurement of sediment properties. The significant results follow:

- A numerical model for simulating the acoustic response of the seabed, accounting for all interlayer interactions, showed that

    1. Sediment cores should be sampled at 0.5 cm intervals to predict the frequency response of the seabed up to 15 kHz with a 1.5% accuracy.

    2. Normal incidence reflection data collected by profilers with different frequency bands can generate reflection coefficients that differ by 50% when certain impedance gradients exist at the sediment-water interface. To ensure that the error for the predicted surficial impedance is within 5% of the in situ impedance, requires collecting reflection data over a band of 500 Hz to 15 kHz.

- Remote acoustic sediment property prediction from wideband FM data sets has advanced rapidly under the CBBL program. The results are the following:

    1. A new method for estimating the vertical impedance profile developed under an ONR research program (Dr. Kravitz - program manager) was successfully tested using data from the CBBL program. The inversion algorithm correctly predicted the variations in impedance profiles to a subfloor depth of 2 meters, the maximum penetration depth of the sediment cores.

    2. Because of energy conversion at the fluid-sediment interface, as shown by the Biot-Stoll porous solid acoustic propagation model, reflection coefficient measurements in sediments with a reflection coefficient greater than -14 dB will underestimate (assuming fluid-fluid interaction in the calculation) the surficial impedance by as much as 10 %. CBBL data sets validate this phenomenon and show that impedance predictions need to be corrected for sandy seafloors.

Publications:

"Analysis of Wideband FM Subbottom Data from Kiel Bay, Germany," S.G. Schock and L.R. LeBlanc, EOS Abstract, Jan 18, 1994 Suppl., Ocean Sciences 94, San Diego.

"High resolution volume backscattering and attenuation measurements in marine sediments," Abstract, Meeting of the Acoust. Soc of Amer., June 94

"FM sonar characteristics for normal-incidence sediment classification," S.G. Schock and L.R. LeBlanc, JASA 96(5) Pt. 2, Nov 1994, p.3222.

"Correlation of acoustic impedance and volume scattering with sediment mean grain size and bulk density, D.L. DeBruin, L.R. LeBLanc and S.G. Schock, JASA 96(5), Pt. 2, Nov 1994, p.3223.

"Normal incidence sediment classification using wideband FM pulses in Eckernförde Bay," S.G. Schock, Lester LeBlanc, Darryl DeBruin and Lachlan Munro, Proceedings of the Workshop Modelling Methane-Rich Sediments of Eckernförde Bay, 26-30 June 1995, Eckernförde, FWG-Report 22.

"Full Spectrum sediment property predictions near the Dry Tortugas and Marquesas," S. G. Schock, L.R. LeBlanc and D. DeBruin. Abstract. 1st SEPM Congress on Sedimentary Geology, St. Pete Beach, August 13-16, 1995.

"Classification of marine sediments using a fuzzy logic impedance inversion model" D.L. DeBruin, Ph.D. Dissertation, Florida Atlantic University, 1995.

"Sediment classification of the seafloor using the chirp sonar and the Biot model" P. Beaujean, M.Sc. Thesis, Florida Atlantic University, 1995.

"Development and application of a numerical model for predicting the frequency response of the seabed from impedance profiles" J. Zhang, M. Sc. Thesis, Florida Atlantic University, 1995

TABLE 1: Survey Lines (Key West Cruise)

DATE	LINE NUMBERS	PULSE	TAPE
2/10/95	1	40ms 1.5-7.5kHz	KW-2
2/11/95	2,3,4	40ms 1.5-7.5kHz	KW-3
	Dry Tortugus Grid N-S lines	40ms 1.5-7.5kHz	KW-4
2/12/95	Dry Tortugus Grid E-W lines	40ms 1.5-7.5kHz	KW-5
	5	40ms 1.0-6.0kHz	KW-6
	5	40ms 0.5-3.0kHz	KW-6
	5	40ms 1.0-12.0kHz	KW-6
2/13/95	6	40ms 1.5-7.5kHz	KW-8
	6	40ms 1.5-7.5kHz	KW-9
2/14/95	7	40ms 1.0-10.0kHz	KW-10

TABLE 2: Chronology of Core Site Crossings (within 100 meters of the sonar's track)

Core	Latitude	Longitude	Offset	Time	Tape	Impedance (Pa/m/s)x 10^6
BC15	24°36.480' N	82 °50.902' W	19 m	21:09.48	KW-4	2.989
BC16	24°36.467' N	82°50.911' W	4 m	21:09.38	KW-4	3.119
BC17	24°36.494' N	82°50.917' W	9 m	21:09.59	KW-4	2.809
BC18	24°36.489 N	82°50.913' W	3 m	21:09.54	KW-4	2.830
BC19	24°36.513 N	82°50.890' W	41 m	21:10.15	KW-4	2.830
BC20	24°36.480 N	82°50.900' W	23 m	21:09.48	KW-4	2.989
BC21	24°36.493' N	82°50.905' W	14 m	21:09.59	KW-4	2.809
GC145	24°36.548' N	82°51.562' W	3 m	22:47.13	KW-4	2.622
GC146	24°36.559' N	82°51.569' W	17 m	22:47.23	KW-4	2.606
GC147	24°36.562' N	82°51.566' W	13 m	22:47.23	KW-4	2.606
GC204	24°36.83' N	82°50.88' W	57 m	21:14.53	KW-4	2.639
GC205	24°36.95' N	82°50.996' W	70 m	10:07.38	KW-5	2.768
GC206	24°36.96' N	82°51.576' W	49 m	10:14.45	KW-5	2.692
GC207	24°36.72' N	82°51.92' W	51 m	10:25.28	KW-5	2.390
GC208	24°36.67' N	82°51.99' W	31 m	23:06.30	KW-4	2.542
GC209	24°36.59' N	82°51.96' W	44 m	10:27.49	KW-5	2.527
GC210	24°36.48' N	82°51.77' W	33 m	10:32.52	KW-5	2.606
GC211	24°36.45' N	82°51.82' W	78 m	10:32.10	KW-5	2.469
GC212	24°36.42' N	82°51.96' W	66 m	10:30.15	KW-5	2.622
GC213	24°36.42' N	82°51.98' W	68 m	10:30.15	KW-5	2.622

GC214	24°36.187' N	82°52.02' W	3 m	23:12.55	KW-4	2.639
GC215	24°36.22' N	82°51.97' W	94 m	23:12.26	KW-4	2.639
GC216	24°36.956' N	82°51.968' W	46 m	23:02.30	KW-4	2.851
GC217	24°36.965' N	82°51.737' W	59 m	10:16.53	KW-5	2.557
BC281	24°36.443' N	82°50.904' W	10 m	21:09.16	KW-4	2.768
GC282	24°36.46' N	82°50.93' W	31 m	21:09.32	KW-4	2.711
GC283	24°36.46' N	82°50.91' W	7 m	21:09.32	KW-4	2.711
BC303	24°36.42' N	82°51.54' W	74 m	22:45.30	KW-4	2.749
BC304	24°36.43' N	82°51.57' W	16 m	22:45.35	KW-4	2.768
BC305	24°36.51' N	82°51.47' W	34 m	10:36.30	KW-5	2.749
GC310	24°36.985' N	82°50.455' W	6 m	10:00.52	KW-5	2.639
GC312	24°36.485' N	82°51.453' W	83 m	10:36.36	KW-5	2.711

TABLE 2.b: Impedance comparison between NRL and Chirp data for the Key West survey

Core	NRL imp. (Pa.s/m)x10^6	Chirp imp. (Pa.s/m)x10^6	% error
GC147	2.874	2.606	9.32
GC204	2.643	2.639	.15
GC208	2.977	2.542	14.61
GC210	2.678	2.606	2.69
GC213	2.644	2.622	.83
GC214	2.684	2.639	1.68
GC217	2.604	2.557	1.8
GC283	2.937	2.711	7.69

TABLE 3: Survey Lines (Panama City Cruise)

DATE	LINE NUMBERS	PULSE	TAPE
8/10/93	1,2	20ms 2.0-10.0kHz	PC-1
	3,4	20ms 2.0-10.0kHz	PC-2
	5	20ms 2.0-10.0kHz	PC-3
8/11/93	6	20ms 2.0-10.0kHz	PC-5
8/12/93	7	20ms 2.0-10.0kHz	PC-6
8/13/93	8	20ms 2.0-10.0kHz	PC-7

TABLE 4: Chronology of Core Sites Crossings (Within 100 meters of the sonar's track)

Core	**Latitude**	**Longitude**	**Offset**	**Time**	**Tape**	**Impedance** (Pa/m/s)x10^6
ST-412	29°41.11' N	85°40.53' W	41 m	6:03.51	PC-2	3.264
ST-466	29°40.92' N	85°40.75' W	70 m	3:32.21	PC-1	3.146
ST-468	29°40.91' N	85°40.74' W	75 m	3:31.38	PC-1	3.013

TABLE 4.b: Impedance comparison between NRL and Chirp data for the Panama city survey

Core	**NRL imp.** (Pa.s/m)x10^6	**Chirp imp.** (Pa.s/m)x10^6	**% error**
ST-412	3.365	3.264	3.0
ST-466	3.223	3.146	2.4
ST-468	3.248	3.013	7.0

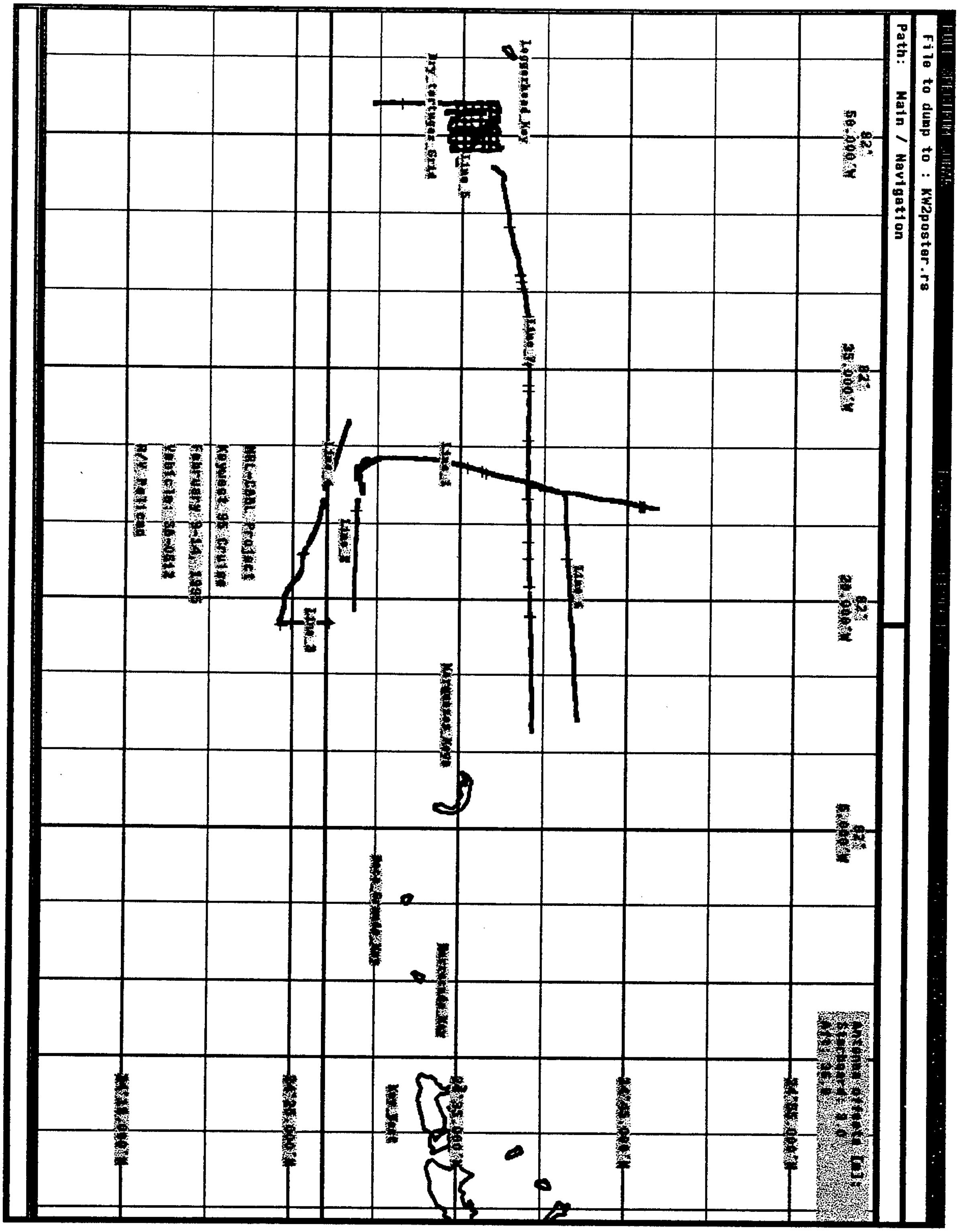
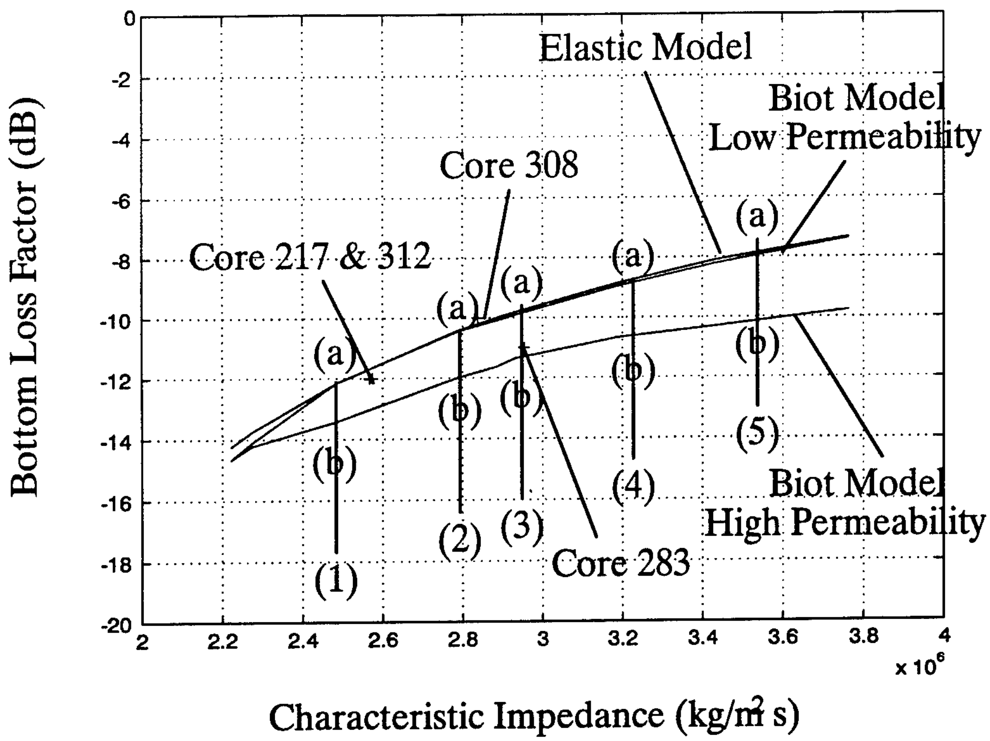


Figure 1: Navigation Tracks for FM Subbottom Survey, Key West, 1995



(1) Sand–Silt–Clay: Porosity=0.663 Mean Grain Diameter=0.0177mm
Poisson Ratio=0.461 Grain Mass Density=2689 kg/m^3
Structure Factor=1.25 Frame Bulk Modulus=1.03*10^{9}Pa
(a) Permeability=5*10^{-14}m^2 (b) Permeability=5*10^{-12} m^2

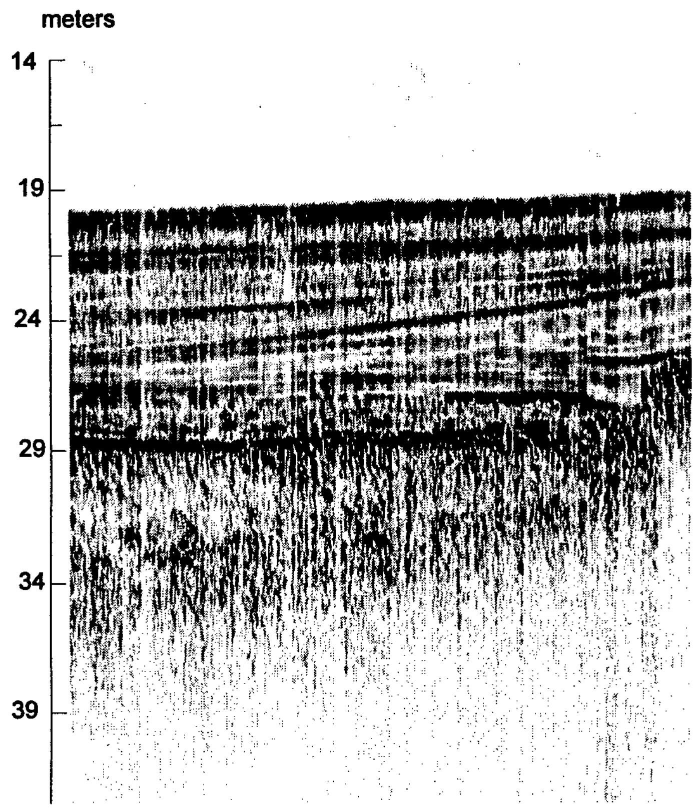
(2) Silt: Porosity=0.562 Mean Grain Diameter=0.0237mm
Poisson Ratio=0.457 Grain Mass Density=2661 kg/m^3
Structure Factor=1.3 Frame Bulk Modulus=1.12*10^9 Pa
(a) Permeability=5*10^{-14} m^2 (b) Permeability=10^{-11} m^2

(3) Silty Sand: Porosity=0.542 Mean Grain Diameter=0.0529mm
Poisson Ratio=0.457 Grain Mass Density=2677 kg/m^3
Structure Factor=1.6 Frame Bulk Modulus=1.4*10^{9}Pa
(a) Permeability=10^{-15}m^2 (b) Permeability=10^{-11}m^2

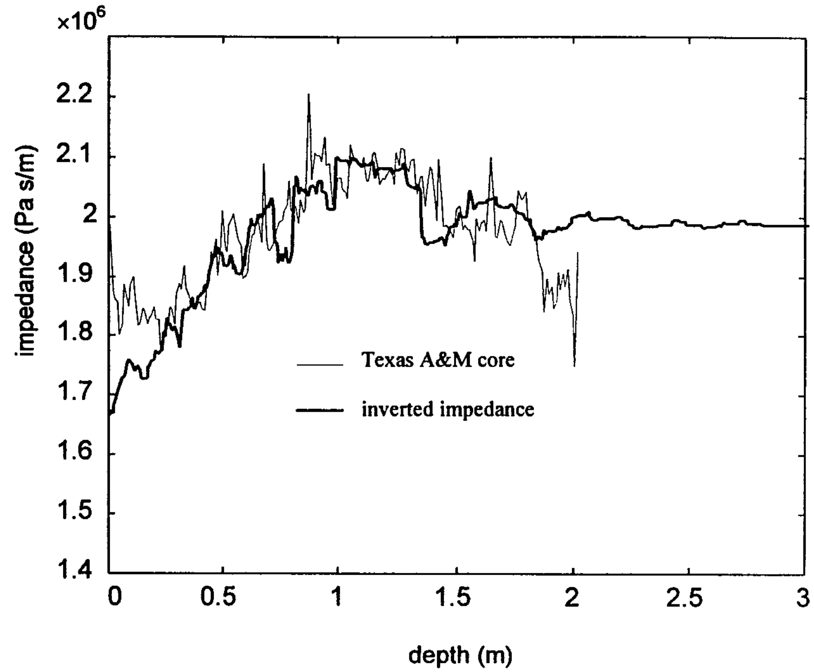
(4) Very Fine Sand: Porosity=0.485 Mean Grain Diameter=0.0988mm
Poisson Ratio=0.453 Grain Mass Density=2680 kg/m^3
Structure Factor=2.0 Frame Bulk Modulus=1.62*10^{9}Pa
(a) Permeability=10^{-15}m^2 (b) Permeability=2*10^{-11}m^2

(5) Fine Sand: Porosity=0.445 Mean Grain Diameter=0.1638mm
Poisson Ratio=0.469 Grain Mass Density=2709 kg/m^3
Structure Factor=2.1 Frame Bulk Modulus=2.05*10^{3}Pa
(a) Permeability=6*10^{-13} m^2 (b) Permeability=5*10^{-11}m^2

Figure 2. Range of Variaton of the Reflection Coefficient as a Function of the Soil Impedance, using the Biot Model.

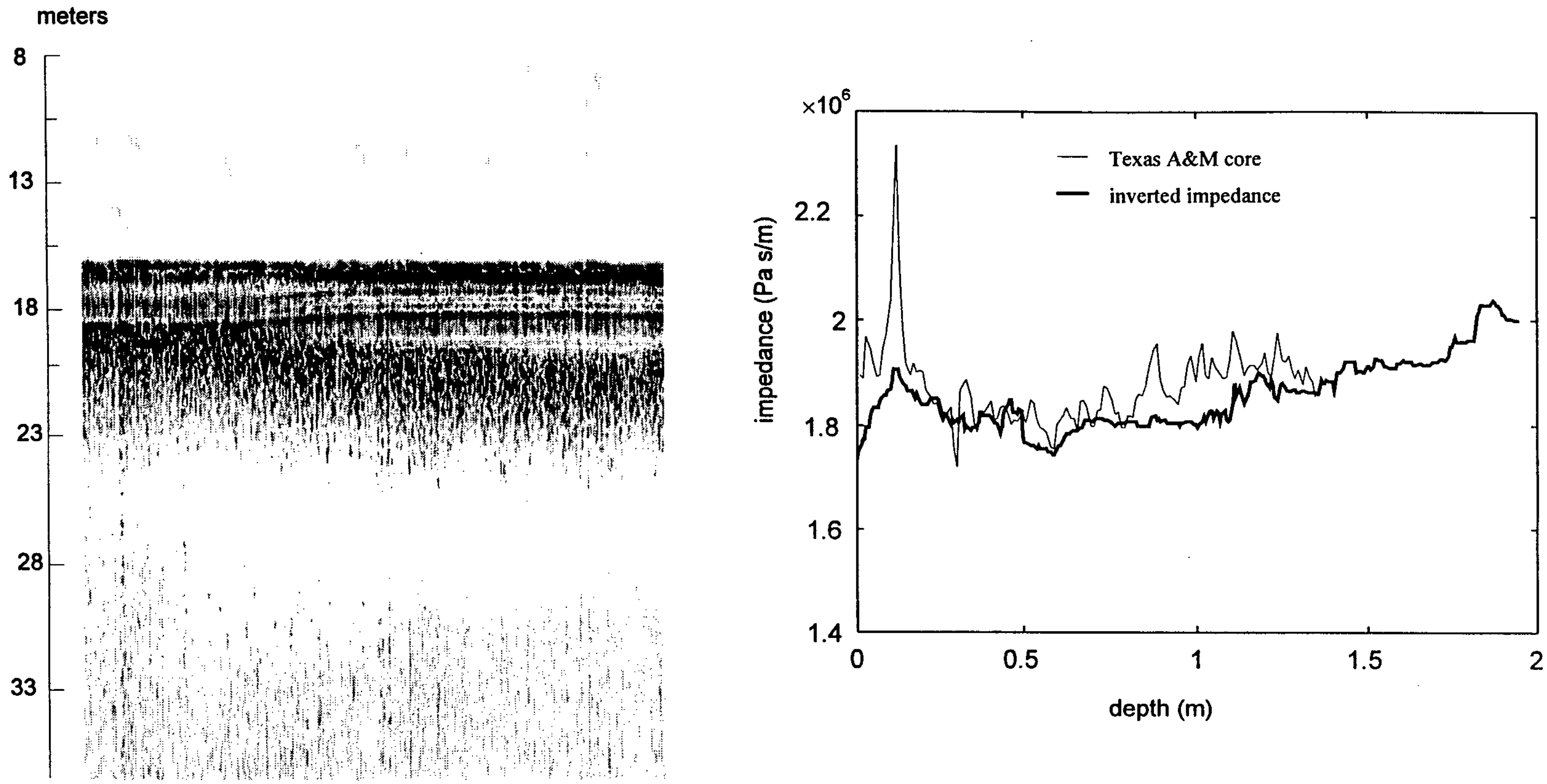


(a) Subbottom image



(b) Impedance profile

Figure 3: a) Subbottom image of core site 331 at Kiel, Germany.
b) measured and inverted impedance vs depth beneath the seafloor



(a) Subbottom image

(b) Impedance profile

Figure 4: a) Subbottom image of core site 336 at Kiel, Germany.
b) measured and inverted impedance vs depth beneath the seafloor

2.14 Effects of Carbonate Dissolution and Precipitation on Sediment Physical Properties and Structure: Pore Water Flux Component (Principal Investigator: A.M. Shiller)

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PROJECT OBJECTIVE

This report describes results from the first six months activity of this contract. The objective of this project is to model the pore water chemistry so as to predict the effects of diagenetic reactions on carbonate dissolution/precipitation (as well as on formation of other phases) and then to compare those predictions with observations of the sediments made by other CBBL participants.

INTRODUCTION

Degradation of organic matter in sediments proceeds via a sequence of thermodynamically-determined reactions (e.g., Froelich et al., 1979). Initially, the organic matter is consumed by normal oxic respiration. When oxygen is used up, certain bacteria can then mediate organic matter oxidation (and obtain energy in the process) using nitrate as the terminal electron acceptor rather than oxygen. As nitrate is used up, then manganese oxides, ferric oxides, and sulfate are all used in sequence. This diagenetic sequence is explained by thermodynamic calculations that show that the first oxidants in the sequence yield more energy per mole of oxidized organic matter than the later oxidants. Crudely put, sulfate reducing bacteria can't effectively compete with us air breathers because we can obtain more energy from a pound of steak than they can.

This thermodynamic sequence of reactions is commonly observed in sediments and has implications for sediment physical properties and structure. There are a number of reasons for this. First, the various oxidative pathways can generate or consume protons, depending on the particular oxidant involved. For instance typical aerobic respiration generates protons whereas anaerobic respiration utilizing manganese oxides consumes protons. This consumption or production of protons also means that organic matter degradation can drive carbonate dissolution or precipitation in the sediments. In nearshore carbonate sediments (where productivity and hence sedimentary diagenesis rates are high) this could be an important factor in affecting sediment physical properties and structure.

A second way in which organic diagenesis can affect the sediments relates to the production of ferrous iron (Fe^{2+}) during the use of ferric oxides to oxidize organic matter. In sulfide-rich waters (as anoxic pore waters are prone to be), the ferrous iron is precipitated as a sulfide. This

produces a new phase in the sediments which, depending on its prevalence, may or may not affect sediment properties. Also, the formation of solid iron sulfide ties up dissolved sulfide, preventing it from diffusing to the oxic layer of the sediments where its oxidation would produce protons which could then result in carbonate dissolution.

A third effect of organic diagenesis on sediment properties can happen when sulfate runs out in anoxic pore waters. Organic matter diagenesis can then proceed via methane fermentation. In instances where there are very high amounts of organic matter in the sediments, this can result in the formation of methane bubbles or pockets in the sediments at fairly shallow depths. The effect on sediment physical properties and structure in such cases is quite obvious.

An additional effect of organic diagenesis relates to the release of phosphate. Under certain conditions phosphate can precipitate to form phosphatic authigenic minerals such as apatite (a calcium fluor-phosphate mineral) and vivianite (ferrous phosphate). For instance, in the shallow, anoxic carbonate sediments of Florida Bay and Bermuda, Berner (1974) reported evidence for apatite formation.

In the CBBL program, it has been the role of the geochemists to come to an understanding of how the various diagenetic reactions affect sediment physical properties and structure in various shallow water environments. At the Key West site, which is dominated by carbonate sediments, the effect of diagenesis on carbonate dissolution and precipitation is the major geochemical process of interest.

PORE WATER FLUX COMPONENT: WORK TO DATE

Measurements by our group during the CBBL Key West campaign included: a) micro-electrode profiles of oxygen, pH, and formation factor across the sediment-water interface, b) flux chamber experiments to examine fluxes of oxygen and nutrients across the sediment-water interface, and c) collection of pore waters and sediments for examination of manganese and iron redox chemistry as well as phosphate chemistry. Initial results were presented by Shiller et al. (1995) at the recent SEPM Congress.

Micro-electrode profiles of box core 141 (Planet site) are shown in Figure 1. A simple diffusion model of the O_2 profile suggests a flux of 530 μmol O_2 cm^{-2} yr^{-1} into the sediments. This is quite high compared to other environments where similar measurements have been made, for example Jahnke (1990) reports an O_2 flux across Santa Monica Basin sediments of 13 μmol O_2 cm^{-2} yr^{-1} and Cai et al. (1995) report a flux of 58 μmol O_2 cm^{-2} yr^{-1} for California rise sediments. Of course, these other locations are deeper and less productive than the shallow Tortugas sediments and the differences are not unreasonable.

One might ask how anoxia can be maintained so close to the sediment-water interface in an area where there is evident bioturbation. The answer lies in the high rate of oxygen consumption. If an organism were to aerate the sediments to a depth of 10 cm, our measured rate of oxygen consumption indicates that it would only take a day and half to deplete the pore water oxygen.

This high rate of oxic respiration also indicates why, in a highly productive area, the sediments are nonetheless poor in organic carbon (typically ~0.5% organic C).

The micro-pH profile shows a significant decrease in the upper cm of the sediment core. This is mainly a result of proton generation during oxic respiration and sulfide oxidation. Preliminary calculations suggest that the pH decrease in the upper 2 mm is actually slightly lower than would be predicted from changes in O_2. While this suggests that the pH was partly buffered by dissolution of $CaCO_3$, the amount of carbonate dissolution required to do this is quite small. Interestingly, preliminary observations by C. Brunner indicate the presence of re-crystallized aragonite in the core below the upper cm. Probably, the carbonate that we predict is dissolving in the upper cm is some of this aragonite which forms deeper in the core and is then brought to the sediment-water interface by bioturbation.

The micro-formation factor profile reflects changes in porosity on a fine scale. These data, which are needed for modeling of the micro-oxygen profile, indicate that porosity was still ~80% at 1 cm.

Flux chamber experiments did not work as well as hoped. This is due in part to having to do the experiment "cold", that is, without prior knowledge of the rates involved. Additionally, operational difficulties at sea may prevent us from having readily interpretable results from these experiments.

Pore waters and sediments were obtained from half a dozen cores during the Key West campaign. All groups doing pore water work had problems obtaining pore waters from the upper few cm of the cores due to the nature of the coarse uncompacted sediments which resulted in channeling of pore waters along the sides of sub-core tubes. These samples have not yet been analyzed, though some preliminary measurements have been made of iron in the carbonate fraction of the sediments.

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Figure 1a. Oxygen microelectrode profile in Dry Tortugas box core 141.

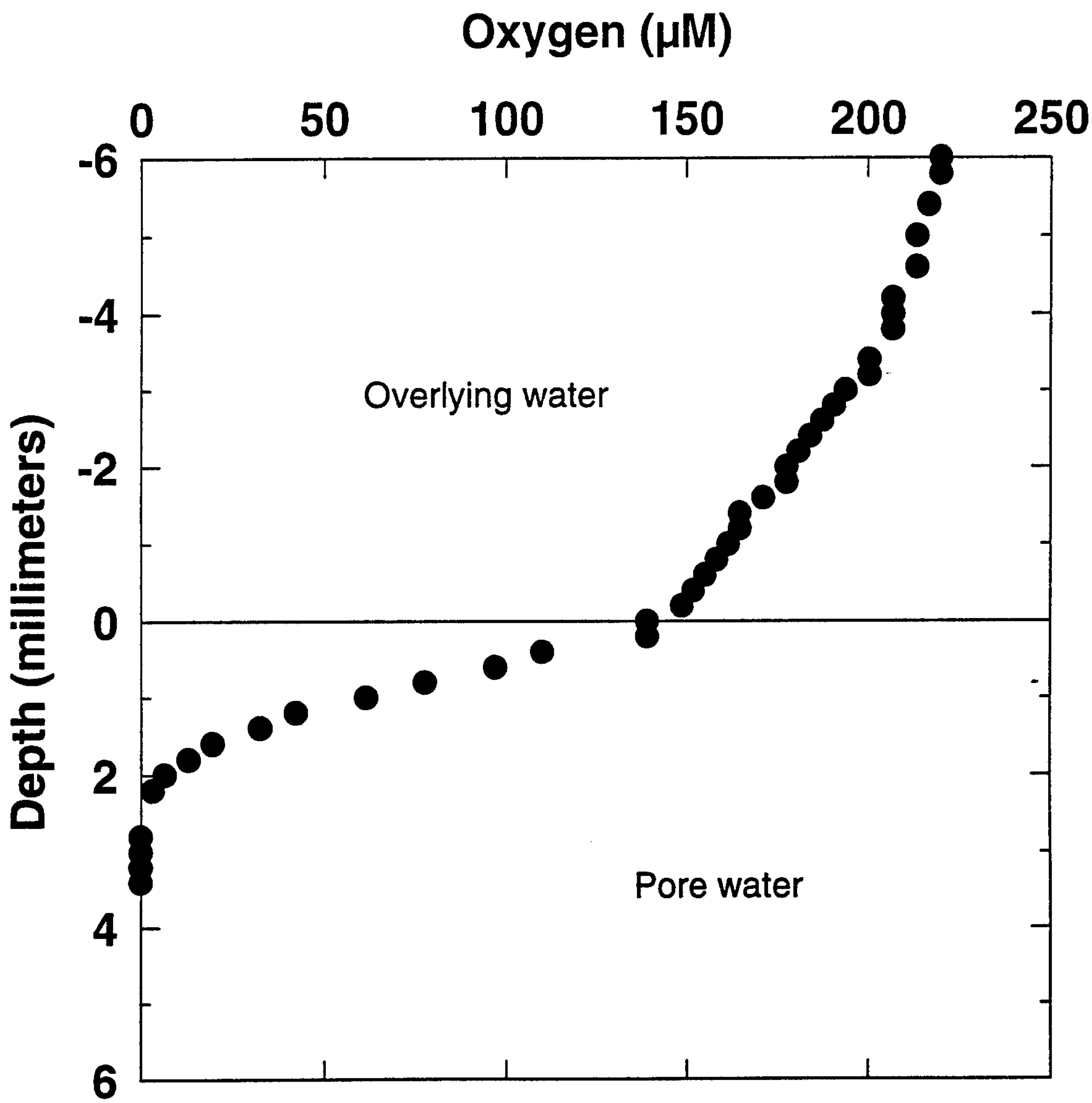


Figure 1b. pH microelectrode profile in Dry Tortugas box core 141.

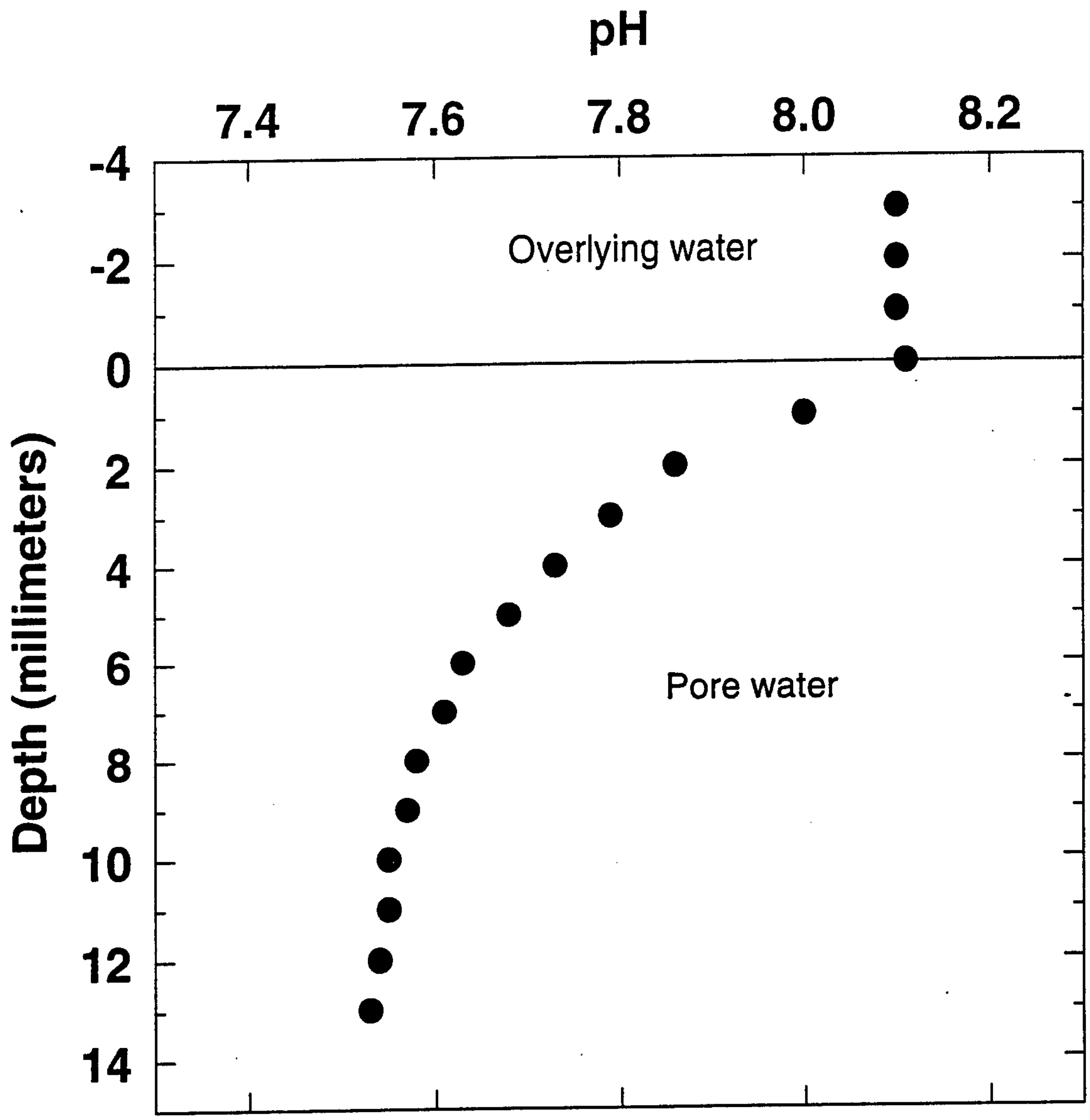
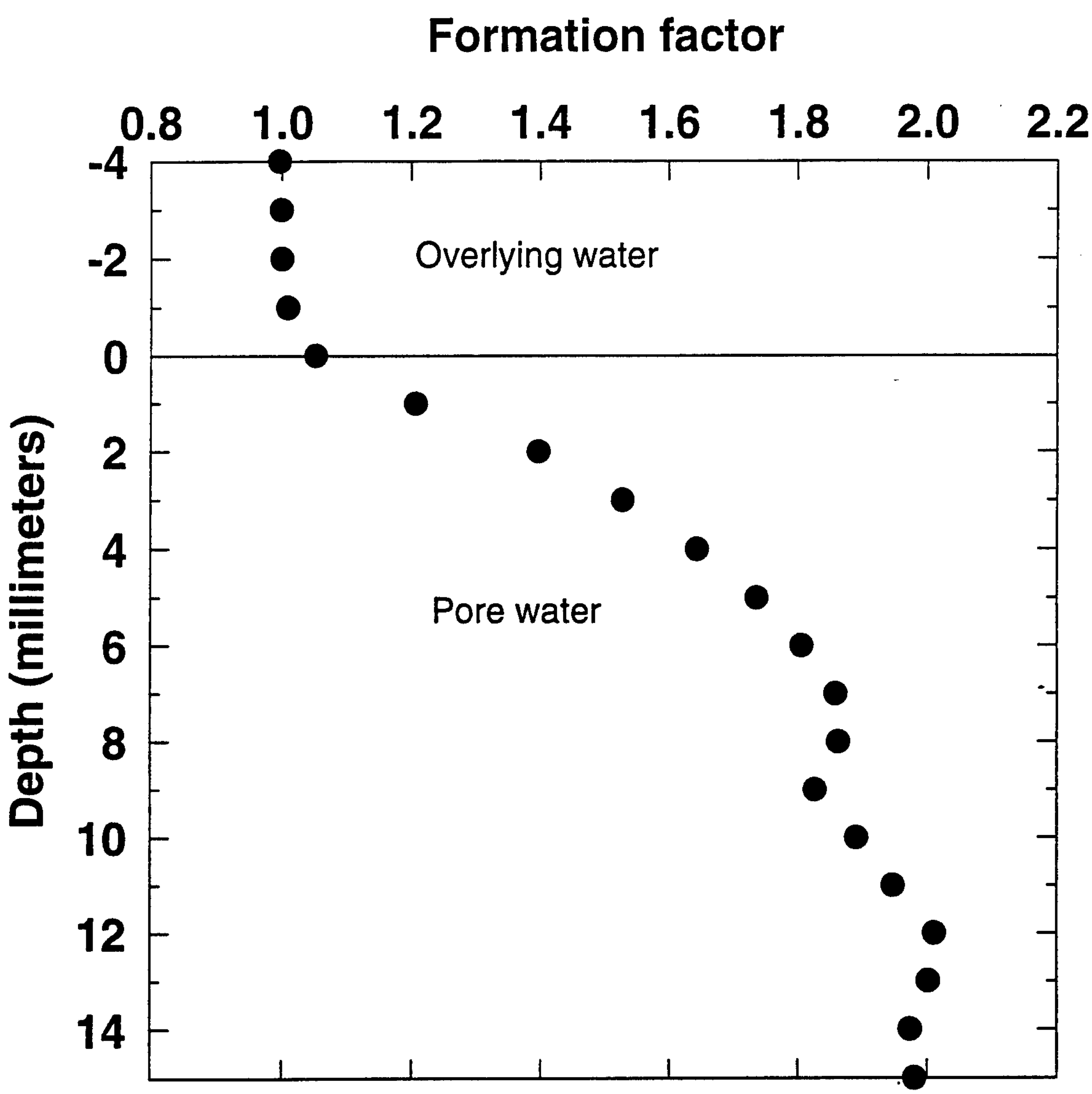


Figure 1c. Micro formation factor profile in Dry Tortugas box core 141.



2.15 Variability of Seabed Sediment Microstructure and Stress-Strain Behavior in Relation to Acoustic Characteristics (Principal Investigators: A.J. Silva, G.E. Veyera, M.H. Sadd and H.G. Brandes)

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INTRODUCTION

This is the third annual report, covering activities during FY95 of the University of Rhode Island, Marine Geomechanics Laboratory (URI/MGL) research program as part of the Coastal Benthic Boundary Layer (CBBL) program sponsored by the Office of the Naval Research and managed by the Naval Research Laboratory, Stennis Space Center with Michael D. Richardson as Chief Scientist. The focus of the URI/MGL program is on the variability of sediment geotechnical properties and microstructure with particular emphasis on stress-strain behavior and modeling in relation to geoacoustic characteristics.

The third year of this program was a very busy and productive time with: a major involvement in the Key West Campaign research expedition; laboratory testing of sediment samples from Eckernförde Bay, Florida Sand Sheet south of Panama City, FL, and the two study sites west of Key West, FL; participation in the Eckernförde Workshop in June/July, 1995; a poster presentation at the SEPM meeting in August, 1995; progress in both micromechanical and macrostructural modeling efforts, and preparation of several manuscripts, theses, and reports. This report summarizes our activities for the period of October, 1994 through September, 1995.

FACILITIES

Equipment development and refinement continued over the course of last year. These improvements have resulted in several state of the art systems for testing the broad range of sediment collected from the three CBBL study sites. The modifications and improvements are summarized below.

Constant Rate of Deformation (CRD) Consolidation Testing System: A second CRD station has been completed and is in operation, allowing for two samples to be tested simultaneously. Consolidation and permeability testing of Key West samples has begun in conjunction with the continued testing of Baltic Sea sediments.

Triaxial Compression Testing System: Specialized sample preparation equipment and procedures have been developed for performing triaxial strength tests on the very soft Baltic Sea

sediments. Other refinements have been made for testing granular sediments from the Panama City, FL and calcareous sediment from Key West sites.

Non-Contacting Radial Deformation Gauges: The specially designed triaxial cell, fitted with electromagnetic displacement transducers, has been added to our triaxial testing system. Future uses will allow for K_0 strength testing.

Volume Change Device: Volume changes during drained triaxial compression tests may now be measured electronically. This system is more accurate and replaces the need to manually read burettes. The output from this device is read directly by the system's data acquisition program.

Geoacoustic Triaxial Compression Testing System: The waveform generator, power source, and amplifier have been installed. A digital storage oscilloscope remains to be purchased. The acoustic triaxial cell is currently at NRL for repairs and the complete system should be operational by the end of December 1995.

Submersible Internal Load Cell: An internal load cell has been ordered for the triaxial compression testing system. This sensor will improve axial load measurements, especially for the Baltic Sea sediments.

Photography Station: The photography station allows for the proper lighting necessary to clearly document variations in layers and sediment types observed in recovered cores.

Laboratory Computers: A new PC (Gateway 2000) has been purchased for the Multi Sensor Core Logger (MSCL) and general laboratory use. A portable external isk drive has been purchased for the remaining laboratory computers along with increased RAM.

PERSONNEL

During FY94, the MGL research personnel working on the project included: a) Principal Investigator and Project Director, A.J. Silva (Ocean and Civil Engineering); b) three Co-P.I.'s, M.H. Sadd (Mechanical Engineering), G.E. Veyera (Civil Engineering), and H.G. Brandes (Ocean Engineering), c) four graduate students; A. Ag, D. Brogan, A. Gautam (1 semester), P. Pizzimenti and Gabriella Sykora (joined in 7/95); d) three part-time undergraduate students, e) a part-time administrative assistant, and f) various other technical support staff.

RESEARCH CRUISE

S

ix URI/MGL personnel participated in the Key West Campaign research campaign to the Marquesas and Dry Tortugas sites west of Key West, FL to collect sediment samples for characterization of the benthic boundary layer and for detailed laboratory testing. Our portion of the program was conducted from the R/V Seward Johnson during the period of February 15 through March 3, 1995. Work centered on obtaining undisturbed gravity cores up to 3 m in length using the URI/MGL large-diameter (10.2 cm) gravity corer (LGC) and tripping mechanism, vibracores using the NRL pneumatic corer, box cores using a 50x50x50 cm spade

corer, and grab samples using a Van-Veem grab sampler supplied by NRL. Most sampling was done at the two designated study sites, although some cores were taken in adjacent areas of interest. Coring operations were conducted in close cooperation with TAMU, and all of the cores were processed through the TAMU MSCL at the shore-based facility. The recovered samples were shared among TAMU, URI and NRL (see our cruise[1] report for disposition of individual cores).

A total of 69 gravity cores were obtained, 27 in the Marquesas area, 40 in the Dry Tortugas area, and 2 at intermediate locations. Total recovery of LGC cores, not including bagged samples, was 120.5 m. In addition, 12 box cores, 4 grab samples and 10 vibracores were obtained, for a total of 95 successful sampler deployments. All box cores were fully processed and/or subsampled onboard by URI and TAMU personnel. The URI group took subsamples for consolidation, permeability, triaxial, density and index property testing, and conducted vane shear measurements at various depths. In addition, during this leg of the cruise, other groups also obtained data from in situ penetrometer tests, piezocone tests and acoustic experiments.

Cores returned to URI have been logged, processed and subsampled, and the laboratory testing program is now well underway. Preliminary results indicate significant vertical and lateral material property variations at both sites. In general, both the geotechnical and geoacoustic parameters measured thus far appear to fall between those measured at Eckernförde Bay and Panama City, FL. Typical bulk densities range between 1.5 and 1.8 gm/cm^3, water contents between 35 and 60%, compressional wave velocities between 1500 and 1600 m/s, and attenuations between 100 and 300 dB/m at 500 kHz.

GEOTECHNICAL EXPERIMENTAL PROGRAM

Key West Campaign

Core Processing and Physical Properties: Thirty-three (33) gravity cores obtained during the February 1995 cruise were returned to the MGL for detailed laboratory tests and analysis. Seventeen (17) of these cores (KW-SJ-GC-168, 178, 188 and 190 from the Marquesas site; 226, 232, 234, 269, 285, 288, 290, 293, 295, 301, 313 and 321 from the Dry Tortugas site and 326 from the Rebecca Shoals) were logged using the URI/MGL MSCL before processing. Since the gamma ray attenuation coefficients for these sediments are significantly different from that of aluminum (typically used for calibration) special calibration procedures were necessary for evaluation of bulk density. Results from the MSCL measurements presented in Fig. 1 indicate bulk densities ranging from 1.7 to 2.0 g/cm^3 with most values at about 1.9 g/cm^3. These relatively high bulk densities are attributable to the large aragonite content (specific gravity = 2.93) of the sediments. In general, the 4 cores from the Marquesas test site and Core 326 from the Rebecca Shoals have somewhat lower bulk densities (about 1.8 g/cm^3) compared to the Dry Tortugas site (about 1.9 g/cm^3).

[1] Key West Campaign Cruise Reports by M.D. Richardson and L. Cole, April, 1995; Section 7.

Compressional wave speeds range from 1500 m/s to 1600 m/s with cores from the Marquesas site and Rebecca Shoals having velocities of about 1500 m/s while the Dry Tortugas cores have velocities of about 1600 m/s. Velocity variations in each core correlate with general variations in the bulk density. There is significant compressional wave attenuation in most cores with the attenuation coefficient ranging from 50 to 300 dB/m with most values falling between 100 and 200 dB/m.

Eight cores were vertically extruded while the remaining were processed horizontally. Sediments varied from carbonate sands to clays mixed with varying amounts of shell fragments and shell clusters. Water content, bulk density and vane shear measurements were made at regular intervals and numerous subsamples were obtained for classification, consolidation/permeability and triaxial testing. Typical water contents (Fig. 1), corrected for a salt content of 35 ppt, are in the range of 35 to 55% below the top 25 cm while in the top 25 cm water contents are generally higher (up to 75%). In addition to the steep gradients in the upper 25 cm, in some cores there is significant vertical variability in water contents and density downcore (see Fig. 1b).

Shear strengths from gravity cores obtained using a mini vane shear device (adapted to a Brookfield Viscometer), range from 2 to 30 kPa and generally increase with depth. Due to a significant amount of shell fragments in some cores, shear strength measurements were possible only at very few locations. Measured shear strengths of surficial sediments (0-10 cm) obtained from box cores were in the range of 0.05 to 5 kPa.

Physical property tests have been done on several samples from the cores KW-SJ-GC-166, 178, 182, 192, 214, 216, 313 and 326 (Table 1). . Measured specific gravities range from 2.71 to 2.90 with most values near 2.79. Liquid limits (LL) range from 35 to 53% and plasticity indices (PI) from 4 to 25% (ASTM D-4318) excluding core 326-GC. Many of the samples were turned out to be nonplastic. Core 326, which has a larger clay content than others tested, has an average LL of 49% and PI of 20%. Grain size analyses (sieve analysis to ASTM D 422 for the coarse fraction and by the pipette method, (Folk, 1974) for the fines) were performed on eight samples from core 313-GC (Table 2). Most of the sediment consists of fine to medium sand size fraction, fines (< 62 microns) between 13 to 36% and a small amount of coarse sands. Grain size analyses on three other cores are in progress.

Carbonate Contents: Carbonate contents of three Key West cores were determined using the coulometer method. The measured weight per cent of calcium carbonate in the cores ranged from 85 to 95 % over the study sites. Also, these values were nearly constant down core to depths of 3 meters.

Consolidation and Permeability: Constant rate of deformation compressibility tests and permeability tests were performed on two samples from core KW-SJ-GC-313 at 5-9 cm and 45-49 cm depth. The compression data (Fig. 2) show that the sediments have very low compression indices (0.23 to 0.25) and large preconsolidation stresses, 30 kPa and 72 kPa, respectively. The compression curves indicate some degree of sample disturbance. The stress state ratio (preconsolidation stress normalized with effective overburden stress) for the samples are 50 and

20 kPa respectively reflecting the high degree of cementation and/or interparticle bonding. The permeabilities are relatively large for the very low void ratios of the samples and showed a linear relationship between void ratio and log of permeability. The in situ void ratios determined from water content measurements on the samples were 1.35 and 1.15. At these void ratios the permeabilities were essentially the same at about 6×10^{-6} cm/s.

Strength Testing: Four isotropically consolidated undrained strength tests were performed on Key West sediments using two samples from the Marquesas test site (Core KW-188) and two from the Dry Tortugas test site (Core KW-313). During shear, the samples all exhibited initially large positive pore pressures and continually increasing stresses which is not uncommon in high-carbonate content sediments. Preliminary shear test results are shown in Table 3 and deviator stress paths for two samples from the Dry Tortugas site are shown in Fig. 3, with a friction angle of 43°. It is possible that this relatively high friction angle is due in part to cementation effects.

Panama City, FL, Florida Sand Sheet

The laboratory program for the Panama City sediments consisted of subsampling 8 cores and performing selected laboratory tests. Subsampling provided 54 bag samples, 12 undisturbed consolidation samples (eight at 6.35 cm diameter and four at 5.08 cm diameter), and seventeen 5.08 cm diameter undisturbed triaxial samples. Grain size and strength tests were conducted on the subsamples and a special test was designed to find some acoustic properties. Due to the relatively coarse nature of the sediment grain size analyses consisted of sieve tests on dry samples. The sediments are generally classified as a well graded coarse to fine sand. The average grain size across all 8 cores was 0.56 mm. Visual inspections reveal that they consist mostly of shell and coral fragments with some quartz grains.

Three isotropically consolidated drained strength tests were performed on samples from core 575-PC-GC. The samples failed in a dilative mode which is typical of relatively dense sands. The average initial tangent modulus was 9100 kPa. Pertinent results are shown in Table 4. The average void ratio at failure was 1.71 and the average critical void ratio (void ratio associated with no volume change during shear) was 1.77. Angles of internal friction ranged from 44° to 51° with an average of 47°.

Acoustic tests were performed on the sediments to measure compressional velocity and attenuation. Samples were divided by grain size, saturated with de-aired water in a loose state an then compressional velocity and attenuation measurements were made. The samples were then densified and the same measurements were repeated. As expected, velocity was found to increase with density and attenuation increased with grain size, with significantly larger attenuation for grain sizes above 1 mm.

Baltic Sea, Eckernförde Bay, Germany

Triaxial testing of Baltic Sea sediments was continued, providing additional data on stress-strain and strength characteristics. Sample preparation and set-up procedures were further developed and refined for these extremely soft sediments. Specialized equipment designed for aiding in set-

up allows for an undisturbed sample to be placed within a triaxial cell, confined at all times, with no manual contact and minimal disturbance. Seven Consolidated Isotropically Undrained (CIU) strength tests were conducted using the improved procedures (Table 5). The stress-strain behavior of Baltic Sea sediments are characterized by well defined failures and low angles of internal friction (Fig. 4). Peaks in the deviator stress occur at small axial strains ranging from 1.4 to 4.3% (Table 5). The average angle of internal friction was found to be 22° with no cohesion intercept. The secant modulus defined as the slope of the stress-strain curve from the origin to the value of one half the maximum deviator stress, was found to range from 103 to 480 kPa. With the addition of an internal load cell and special testing procedures, the elastic modulus will be better defined. Despite the high water contents (generally over 200%), high plasticity, high compressibility and high organics, Baltic Sea sediment behaves as a normally consolidated clay with a low friction angle. These findings are included in a M.S. thesis by Brogan (1995).

Modeling

Geoacoustic Micromechanical Modeling

Although this part of our program was not funded for FY95, we continued significant activities during most of FY95. A paper was presented by M. Sadd at the ASA meeting in Austin, TX (November, 1994) and an experimental program begun in the summer of 1994 was completed. The M.S. research by Mr. Gautam, funded in part by the CBBL program in the previous year, was also completed during FY95. These results have been incorporated in a manuscript that is ready for publication. In addition, M. Sadd has maintained a keen interest in the program and is continuing development of the constitutive model.

At the request of M. Richardson, we have organized a special workshop "Sediment Geoacoustical and Geotechnical Constitutive Modeling" convened at URI on November 13-14, 1995. The purpose was to bring constitutive modeling efforts back into the CBBL program and leverage this into a more substantial ONR program. The workshop generated a tremendous amount of interest and interaction among participants.

Macrostructural Finite Element Modeling

The objective of this portion of the program has been to develop a numerical capability for predicting the macrostructural, mechanical behavior of sediments that are of interest to the CBBL SRP. Efforts during FY95 have centered on further development of the URI/MGL finite element code *GEO-CP* and on laboratory data interpretation from the Eckernförde, Panama City, FL and Key West sites. Of special interest are mine burial prediction and the evolution of pock mark features in the seabed. Initial findings indicate that the soft, fine-grained Baltic sediments are best treated using time-dependent plasticity-based critical state models. Average constitutive parameters determined for these sediments include: a) compression index = 4.0, b) recompression index = 0.5, c) permeability = 4×10^{-6} cm/s, and d) friction angle = 22°. Additional strength tests will be conducted to determine the remaining parameters. A time-independent elastic model will be sufficient for the coarse grained sands at the Panama City, FL site. Triaxial tests are now underway to determine the elastic parameters from undisturbed and

reconstituted specimens. From preliminary testing of the Key West sediments, it appears that the material is very stiff with signs of cementation and/or high interparticle bonding along with unusual pore pressure response. It is not yet clear which type of constitutive model might be appropriate for this type of material and whether extensions or modifications to the existing models in *GEO-CP* might be necessary.

SUMMARY AND CONCLUSIONS

The third year (FY95) of our research has been extremely busy and productive for the URI/MGL portion of the CBBL program. The work is briefly summarized below and the publications are listed elsewhere.

1. We had a major role in the very successful sediment sampling program for the Key West Campaign.
2. Essentially all aspects of the geotechnical laboratory experimental program have produced substantial results. With special procedures and techniques we have the ability to conduct triaxial stress-strain/strength tests, compressibility tests, and permeability measurements of the soft, high porosity sediments from Eckernförde Bay. These organic rich sediments behave as low strength (friction angle of 22_) similar to normally consolidated clays with relatively low permeability of about 4×10^{-6}cm/s and high compression index of about 4.0. The Panama/Florida Sand Sheet sediments behave as a dense sand with high friction angle of about 47_. The Key West carbonate sediments (approximately 90% carbonate) have unusual stress-strain and pore pressure responses in the triaxial compression test and high friction angle (43_); which may be caused by cementation and/or very high interparticle bonding. Testing will be continued.

3. Physical and acoustic properties profiles for the Dry Tortugas and Marquesas sites will be useful in correlating vertical variability with subbottom acoustic characteristics.

4. Micromechanical modeling work was scaled back due to funding restrictions but two publications and a M.S. thesis were completed. A special workshop at URI was organized in November, 1995.

5. The macrostructural modeling concentrated on further development of the URI/MGL finite element code *GEO-CP* and preliminary analysis of features such as pock mark evolution in Eckernförde Bay.

SIGNIFICANCE OF RESULTS TO CBBL OBJECTIVES

The geotechnical characterization of the seabed at the three CBBL study sites will be of prime importance in understanding fundamental linkages between sediment substrata variability, microstructure/fabric characteristics, physical/engineering properties, and geoacoustic behavior. The stress-strain-time, strength, and geoacoustic sediment properties including stress state, remolding effects, and effects of natural constituents such as gas, organics, and cementing agents,

are central and necessary to the development of micromechanical and macrostructural models for predicting sediment behavior over the range of conditions of interest to the CBBL program. Following are some preliminary results of the geotechnical research. Note that this is "work in progress" and a major part of the data analysis, interpretation, and modeling will be accomplished during the next two years.

Variability: The organic silty clays show dramatic vertical variability of key physical properties in the near-surface zones (0-20 cm) that affect acoustic response. The seasonal migration of methane gas is also of prime importance. The calcareous sediments also show significant variability near the surface as well as distinct layering within the upper 3 m. The shelly sands exhibit less vertical variability, but some lateral variability across the site due to migration of surface materials.

Geotechnical Characterization, Properties, and Behavior: The Eckernförde Bay site has been analyzed and results reported in several reports, theses, and publications; especially the two Geomarine Letters manuscripts (in publication, 1996). The sediments consist of high porosity (86-94%), organic rich (10-20%) silty clays with varying amounts of methane gas. The surface 5-10 cm are characterized by unusually high water contents (400-600%), very low shear strengths (<1 kPa), and pronounced shear thinning behavior. Below that depth sediments are somewhat more competent, exhibiting water contents of 250 to 300%, and higher strengths (>1 kPa). Zones of high and lower densities are present below 50 cm depth. The soft fine-grained sediments have very high in situ void ratios (generally over 6) and are highly compressible. The compression index decreases slightly in the upper 40 cm but remains essentially unchanged at an average value of 3.5 to a depth of 260 cm. Recompression indices range from 5 to 19% of the virgin indices. The preconsolidation stress is consistently higher than the overburden stress, particularly near the surface. Permeabilities at in situ void ratios in the upper 50 cm are about $5x10^{-6}$ cm/s. The effects of anisotropic permeability and overall effects of remolding (that would result from penetration of objects) have also been investigated. The results will be important to understanding the behavior of these unusual materials.

The Florida Sand Sheet sediments are characterized as dense, well graded coarse to fine, shelly sands with high friction angles of 44° to 51°. A special study of acoustic behavior of reconstituted sediments shows the relationship of compressional wave speed and attenuation to density and grain size.

The Key West study sites are in the initial stages of characterization and analysis. The work has generated a very large geotechnical and geoacoustic characterization data base that is of use not only as ground truth for sediment classification systems, but will also serve as input into the macro and microstructural models under development. The initial results indicate significant vertical and lateral property variations throughout the site. Laboratory compressibility, permeability, and strength test results indicate an unusual material that requires further testing and constitutive model development. Results will be very useful in developing models that address the variation in sediment types/conditions at sites of interest to the CBBL SRP.

Micromechanical Modeling: Micromechanical modeling has been conducted in order to provide an understanding of how particular sediment microstructure or fabric effects the propagation of acoustic signals. Using discrete element simulations, specific propagational characteristics including wave speed and attenuation have been related to particular fabric configurations for granular sediments. The research has direct implications to acoustic characteristics.

Macrostructural Modeling: The macrostructural model being developed will be able to provide a means of quantitatively predicting the physical and engineering properties at successive mechanical states. This is of importance when investigating the effect of environmental processes, since "small-strain" acoustic waves propagate with different characteristics (velocity and attenuation) depending on the mechanical state of the material. Basic constitutive models have been selected for the Baltic and Panama City, FL sites and are included in the URI/MGL code *GEO-CP*. Work is now well underway in identifying the necessary input geotechnical parameters. The formulation in *GEO-CP* is also general enough to solve many of the "large-strain" geotechnical problems in the CBBL program that are of interest to the Navy, such as mine burial and detection processes, consolidation and water migration.

PUBLICATIONS

Manuscripts and Abstracts

"Coastal Benthic Boundary Layer Special Research Program: A Review of the First Year", M.D. Richardson, Ed., April 6, 1994. Silva, A., Sadd, M., Veyera, G. and Brandes, Univ. of RI, Oct., FY93 Year-End Report, pp. 181-270.

"Compressibility and Permeability Behavior of High Porosity Surficial Sediments at the CBBL/SRP Baltic Sea Site," Veyera, G., AG A., Brandes, H. and Silva, A., abstract presented at Ocean Sciences Meeting, San Diego, CA, Feb., 1994, Trans., AGU, 75:3, Jan. 18, 1994 (Abs. No. 051G-7).

"Discrete Element Microstructural Modeling of Geoacoustic Wave Propagation in Saturated Granular Seabed Sediments," Sadd, M., Tai, G., Silva, A. and Veyera, G., abstract presented at Ocean Sciences Meeting, San Diego, CA, Feb., 1994, Trans., AGU, 75:3, Jan. 18, 1994 (Abs. No. 051G-8).

"Variability of Geotechnical Properties of High Porosity of Surficial Sediments at the CBBL/SRP Baltic Sea Site," Silva, A., Brandes, H. and Veyera, G., abstract presented at Ocean Sciences Meeting, San Diego, CA, Feb., 1994, Trans., AGU, 75:3, Jan. 18, 1994 (Abs. No. 051G-5).

"Rheological Characteristics of High Porosity Surficial Sediments at the CBBL/SRP Baltic Sea Site," Brandes, H., Veyera, G. and Silva, A., abstract presented at Ocean Sciences Meeting, San Diego, CA, Feb., 1994, Trans, AGU, 75:3, Jan. 18, 1994 (Abs. No. 051G-6)

"Coastal Benthic Boundary Layer Special Research Program: A Review of the Second Year", M.D. Richardson, Ed., July 24, 1995. Silva, A., Brandes, H., Veyera, G., Univ. of RI, Oct., FY94 Year-End Report, pp. 168-177.

"Acoustical Properties of Undisturbed Sands from the West Florida Sand Sheet," Brandes, H. and Silva, A., abstract presented at the ASA Conference, Nov., 1994, 95:5 p. 3246.

A Propagation Model for Wave Motion in Saturated Granular Sediments, Sadd, M., Gautam, A., Silva, A. and Veyera, G., abstract presented at the ASA Conference, Nov. 1994, 96:5, p. 3246.

"Compressibility, Permeability, and Strength Properties of Eckernförde Bay Sediments", A. Silva, H. Brandes and D. Brogan, paper presented at CBBL workshop "Modeling Methane-Rich Sediments of Eckernförde Bay held in Eckernförde, Germany, June-July, 1995.

"Geotechnical Properties and Behavior of Organic Gassy Sediments in Eckernförde Bay, Baltic Sea", A. Silva, H. Brandes and G. Veyera, paper presented at CBBL workshop "Modeling Methane-Rich Sediments of Eckernförde Bay held in Eckernförde, Germany, June-July, 1995.

"Strength Properties of Pressurized and Depressurized Gassy Sediments from Eckernförde Bay", Brandes, H. and Silva, H. Paper presented at CBBL workshop "Modeling Methane-Rich Sediments of Eckernförde Bay held in Eckernförde, Germany, June-July, 1995.

"Geotechnical and Acoustical Properties of Calcareous Sediments at the Dry Tortugas and Marquesas CBBL Sites", Silva, A., Brandes, H. Ag, A., Brogan, D., Pizzimenti, P., and G. Veyera, abstract/poster presented at SEPM Meeting, August 1995, St. Pete Beach, FL.

"Geotechnical Characterization of Surficial High Porosity Sediments in Eckernförde Bay", Silva, A., Brandes, H. and Veyera, G. Geomarine Letters (in press, 1996).

"Consolidation and Permeability Characteristics of Surficial High Porosity Sediments of Eckernförde Bay", H. Brandes, Silva, A., Ag, A. and Veyera, G. Geomarine Letters (in press, 1996).

Theses

"Consolidation and Permeability Behavior of High Porosity Baltic Seabed Sediments", M.S. Thesis by A. Ag, Dept. of Ocean Engineering, Univ. of RI, Dec., 1994.

"Wave Propagation in Saturated Granular Materials", M.S. Thesis by A. Gautam, Dept. of Mechanical Engineering and Applied Mechanics, Univ. of RI, July/Aug. 1995.

"The Strength Behavior of Baltic Sea Sediments", M.S. Thesis by D. Brogan, Dept. of Ocean Engineering, Univ. of RI,, July/Aug., 1995.

"Stress-Strain Behavior of Carbonate Sands", M.S. Thesis by P. Pizzimenti, Dept. of Ocean Engineering, Univ. of RI, expected completion summer, 1996.

Table 1. **Physical Properties of Sediments from the CBBL/NRL Test Sites, Key West.**

Sample Designation	Location	Number of Samples	Specific. Gravity	Liquid Limit (%)[a]	Plasticity Index
166-GC	M	5	2.87 2.85-2.90	43 35-43	12 8-17
178-GC	M	6	2.80 2.76-2.83	44 39-53	18 12-25
182-GC	M	5	2.78 2.75-2.80	44 43-46	16 13-20
192-GC	M	7[b]		40 38-44	13 9-18
214-GC	D	5[c]	2.81	40 38-42	6 4-7
216-BC	D	4	2.75	41 39-45	6 4-8
313-GC	D	7[d]	2.78 2.73-2.82	39	15
326-GC	R	8	2.77 2.71-2.83	49 45-56	20 15-31

Note: average / min - max

a - Corrected for 35 ppt salinity

b - Two samples were non plastic

c - Three samples were nonplastic ; w_L could not be determined

d - Six samples were non plastic ; w_L could not be determined

M - Marquesas D - Dry Tortugas R-Rebecca Shoals

BC - Box Core GC = Gravity Core

Table 2. Texture of Sediments from core KW-SJ-GC-313, CBBL/NRL Test Site, Key West.

Depth (cm)	Coarse Sand (%)*	Medium Sand (%)*	Fine Sand (%)*	Silt & Clay (%)*	Mean Grain Size (ϕ)	Mean Grain Size (mm)
13	4	20	50	26	2.70	0.15
24	3	19	42	36	2.47	0.18
32	6	22	46	26	2.53	0.17
48	28	16	33	23	0.63	0.65
84	3	22	53	22	2.47	0.18
111	9	27	42	22	2.30	0.2
139	28	25	34	13	0.88	0.54
188	3	18	65	14	2.59	0.17

*Coarse Sand > 2 mm

Medium Sand 2 - 0.425 mm

Fine Sand 0.425 -.062 mm

Silt & Clay < 0.062 mm

Table 3. CIU Triaxial Tests, Key West Sediments

Sample	Sample Depth (cm)	Water Content (%)	Consol Stress σ_3' (kPa)	Failure Strain ε_f (%)	Failure Deviator Stress (kPa)	Max. Stress Ratio (kPa)	Pore Pr. Parameter A_f
GC-188	18	36.5	229	8.8	2850	27.3	0.04
GC-188	37	33.0	205	8.9	1300	16.0	0.10
GC-313	32	40.0	26	5.3	58	5.3	0.08
GC-313	128	28.3	110	6.9	415	5.1	0.02

Table 4. CID Triaxial Tests, Panama City Sediments

Sample	Sample Depth (cm)	Consol Stress σ_3' (kPa)	Failure Strain ε_f	Failure Deviator Stress (kPa)	Max. Stress Ratio (kPa)	Failure Void Ratio e_f	Friction Angle ϕ'
GC-575	10	14	3.5	85	6.5	1.72	47
GC-575	10	14	3.2	104	7.8	1.70	51
GC-575	22	31	3.2	139	5.6	1.69	44

Table 5. CIU Triaxial Tests, Baltic Sea Sediments

Test No.	Core No.	Depth (cm)	Consol. Stress σ_3' (kPa)	Failure Deviator Stress (kPa)	Failure Strain ε_f (%)	Friction Angle ϕ'	Secant Mod. E_s* (kPa)	Pore Pr. Parameter A_f
1	252	35	2.30	1.35	3.8	19	134	0.67
2	252	35	2.72	2.30	2.8	24	480	0.48
3	252	35	3.80	2.40	3.5	22	171	0.75
4	238	33	4.30	3.78	4.3	25	386	0.48
5	238	33	4.20	2.45	4.0	19	410	0.73
6	225	20	2.51	1.29	1.8	16	215	0.54
7	225	20	0.83	0.78	1.4	24	103	0.34

* At $\Delta\sigma_{max}/2$

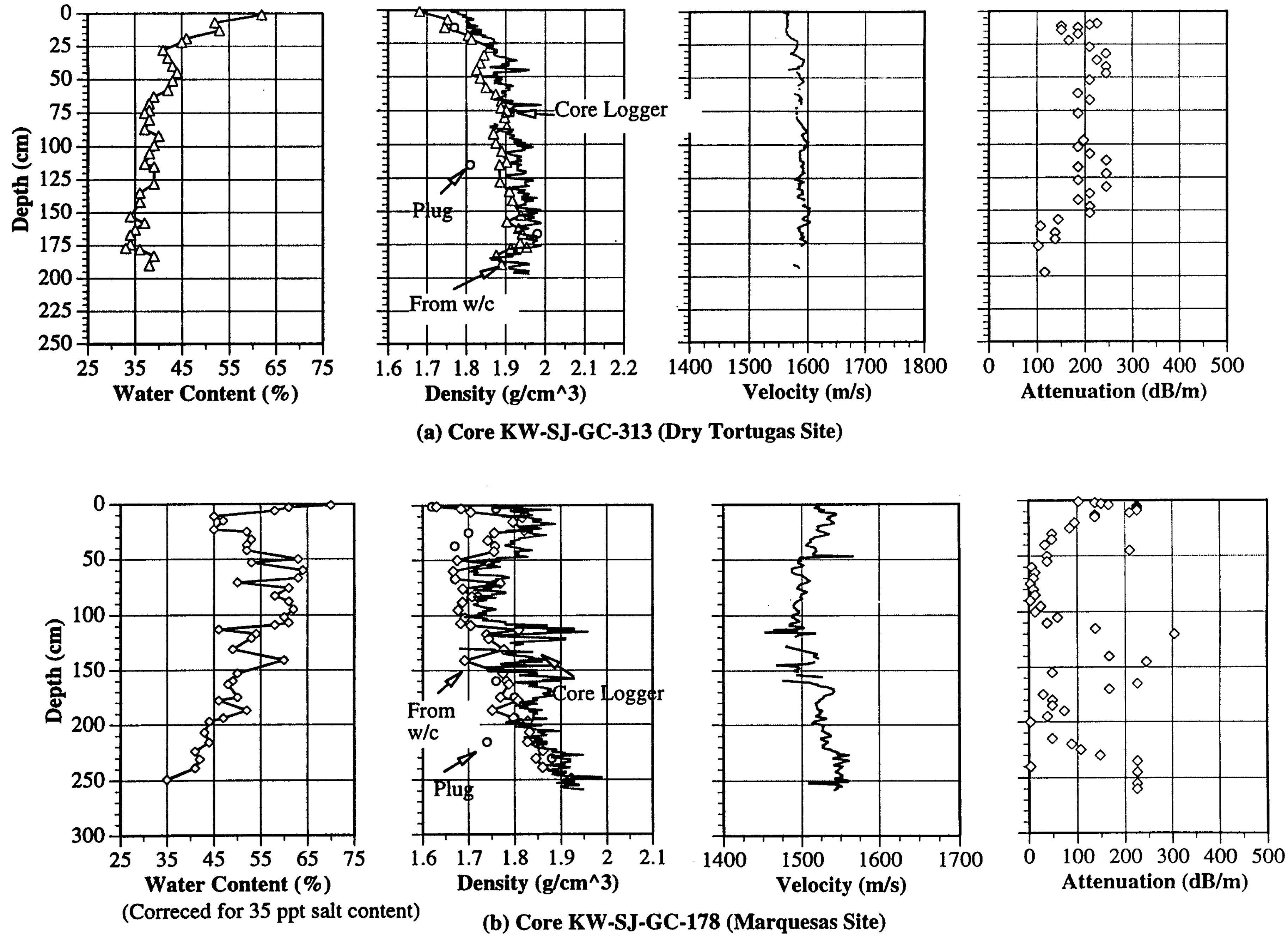
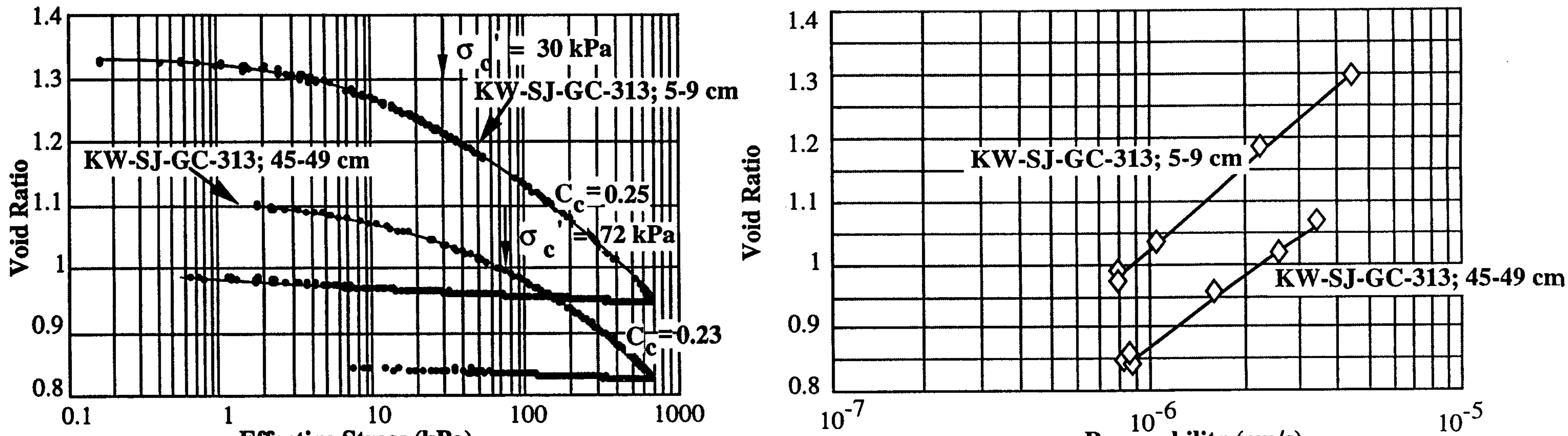


Fig 1. **Physical Property Profiles of Typical Cores; CBBL/ONR; Key West Cruise.**



(a) Compression Curve

(b) Permeability Measurements

Fig 2. Compression Curve and Permeability Measurements; Samples KW-SJ-GC-313; 5-9 cm and 45-49 cm.

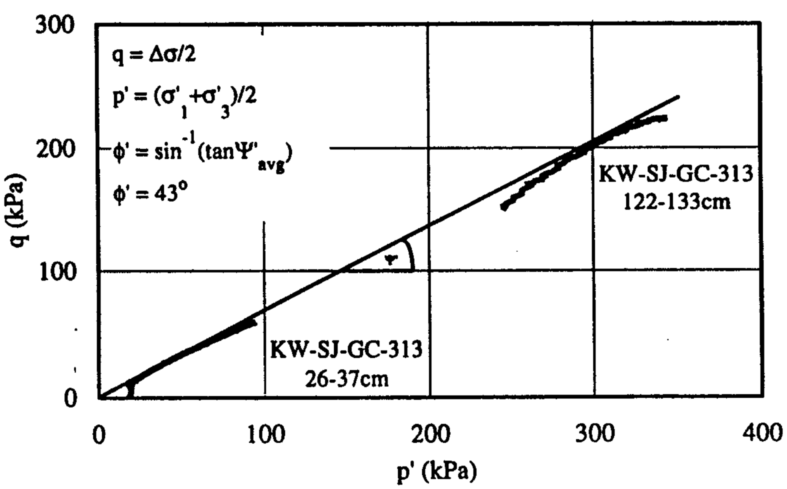


Figure 3. Stress Paths of CIU Strength Tests, Key West, Dry Tortugas Test Site

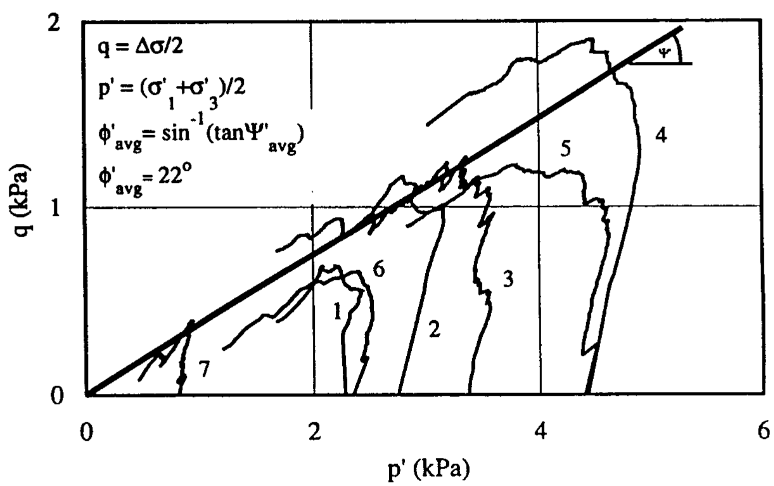


Figure 4. Stress Paths of CIU Strength Tests of Baltic Sea Sediments

2.16 Experimental and Theoretical Studies of Near-Bottom Sediments to Determine Geoacoustic and Geotechnical Properties (Principal Investigator: R.D. Stoll)

FY 95 YEAR-END REPORT

Coastal Benthic Boundary Layer Special Research Program

Grant No. N00014-93-1-6003

EXPERIMENTAL AND THEORETICAL STUDIES OF NEAR-BOTTOM SEDIMENTS TO DETERMINE GEOACOUSTIC AND GEOTECHNICAL PROPERTIES

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January 2, 1996

INTRODUCTION

Our participation in the CBBL program during FY-95 was limited to participation in the workshop "Modelling Methane-Rich Sediments of Eckernforde Bay," June, 1995 and some additional analysis of data obtained earlier in the 1993 Eckernforde and Panama City experiments. However, we did have the opportunity to participate in an LDEO-SACLANTCEN-FWG experiment at the Eckernforde Bay site during the week just prior to the workshop. During this experiment new data on seafloor penetration resistance was obtained at a number of sites where prior work had been carried out under the CBBL program. Comments on some of the data obtained in these new experiments is included in this report.

ECKERNFORDE WORKSHOP

Our contribution to the proceedings of the Eckernforde workshop "Measuring near-bottom shear wave velocity using Love waves," by Robert D. Stoll and E. O. Bautitsta is included as Appendix I to this report. A more detailed description of the use of Love waves for seafloor exploration is given in [1]. As can be seen from either paper, the use of Love waves to study near-bottom sediment properties can result in high resolution determination of shear-wave velocity versus depth in the first few meters of the sediment column. Since one of our main objectives was to relate insitu shear-wave velocity to insitu shear strength, the data obtained from the Love wave experiments is very useful in making direct correlations with quasistatic cone penetration results obtained using our seafloor penetrometer. The latest version of the seafloor penetrometer, which was developed early in the CBBL program, is capable of penetrating 2 m into the bottom and is sensitive enough to measure the very low resistance of the soft Eckernforde mud and yet rugged enough to penetrate compact sand.

PENETRATION TESTS

During the week prior to the Eckernforde workshop, we performed a number of penetration tests in Eckernforde Bay at several sites including the NRL tower sites and several positions along

the "Schock" line. These penetration tests were done in conjunction with tests of the new expendable dynamic penetrometers that are being developed jointly with SACLANT Undersea Research Center [2]. The penetration curves in Fig. 1 are for the NRL tower site while those in Fig. 2 are for several stations along the Schock line. The sediments at all the sites shown in Figs. 1 and 2 contain a significant amount of fine grained material and so the response during the quasistatic penetration test is essentially controlled by their "undrained " shearing strength. Hence, the cone penetration resistance was converted directly to undrained shear strength for the plots shown in Figs. 1 and 2.

The penetration tests in these experiments were performed using the same 60 cm long penetrometer that was mounted on the self-righting sled used in the 1993-4 experiments except that the unit is now mounted on a small, weighted frame that is is lowered directly to the bottom from an anchored ship. As can be seen from Fig. 1 the spread of values for the NRL site is similar to the results obtained from vane shear tests that were performed by divers at that site. (e.g. see Fig. 4 of Ref [3]) with values increasing more or less linearly with depth. In contrast, the mean shear strength does not increase uniformly with depth at the stations along the Schock line but rather tends towards a constant value with local variation as shown in Fig., 2.

The results of penetration tests such as those shown in Figs. 1 and 2 are being used to derive correlations between shear strength and shear-wave velocity and shear strength and deceleration of our dynamic probe.

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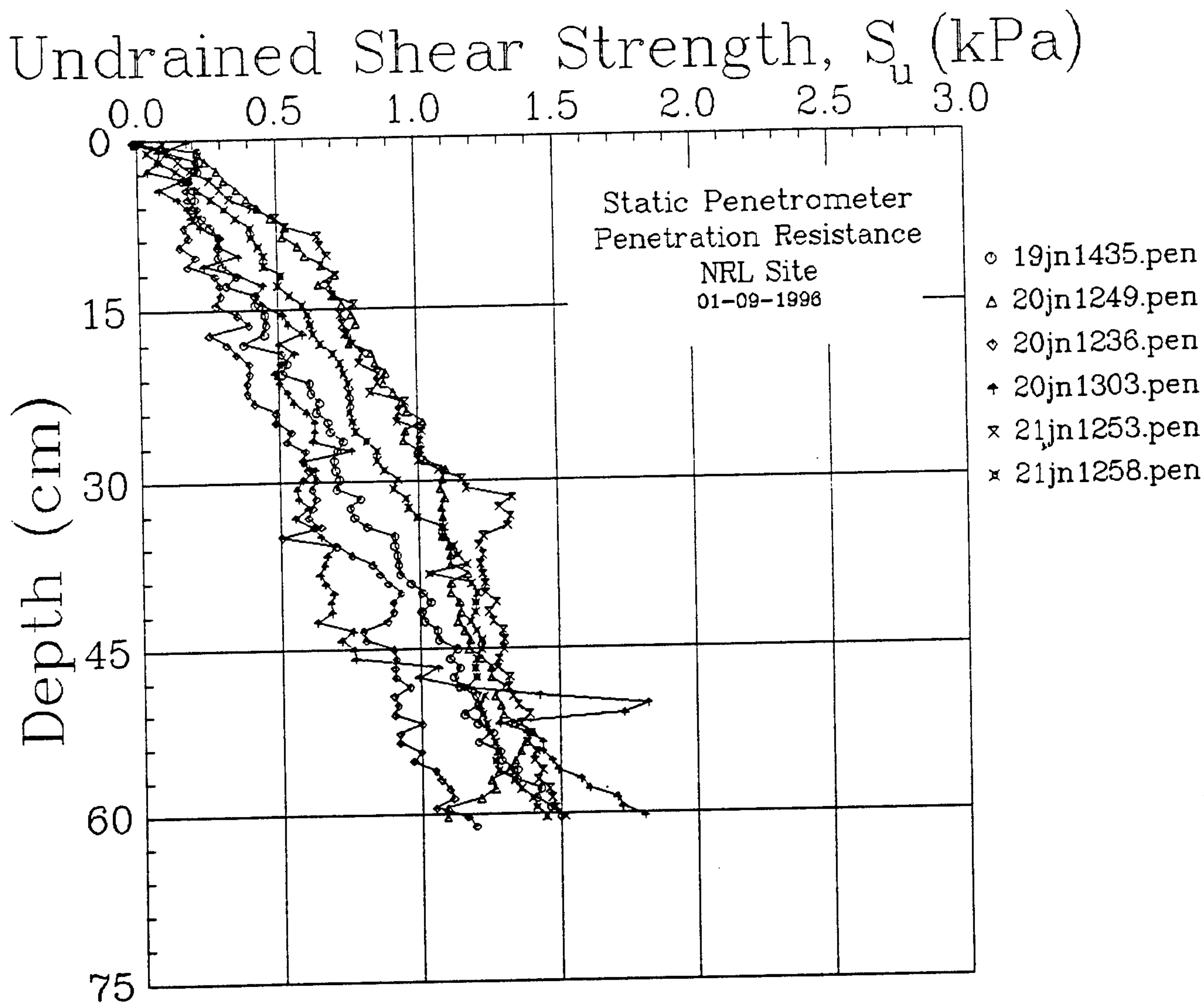

Fig. 1. Undrained shear strength determined from quasistatic cone penetrometer tests at 5 locations near the NRL tower sites in Eckernforde Bay.

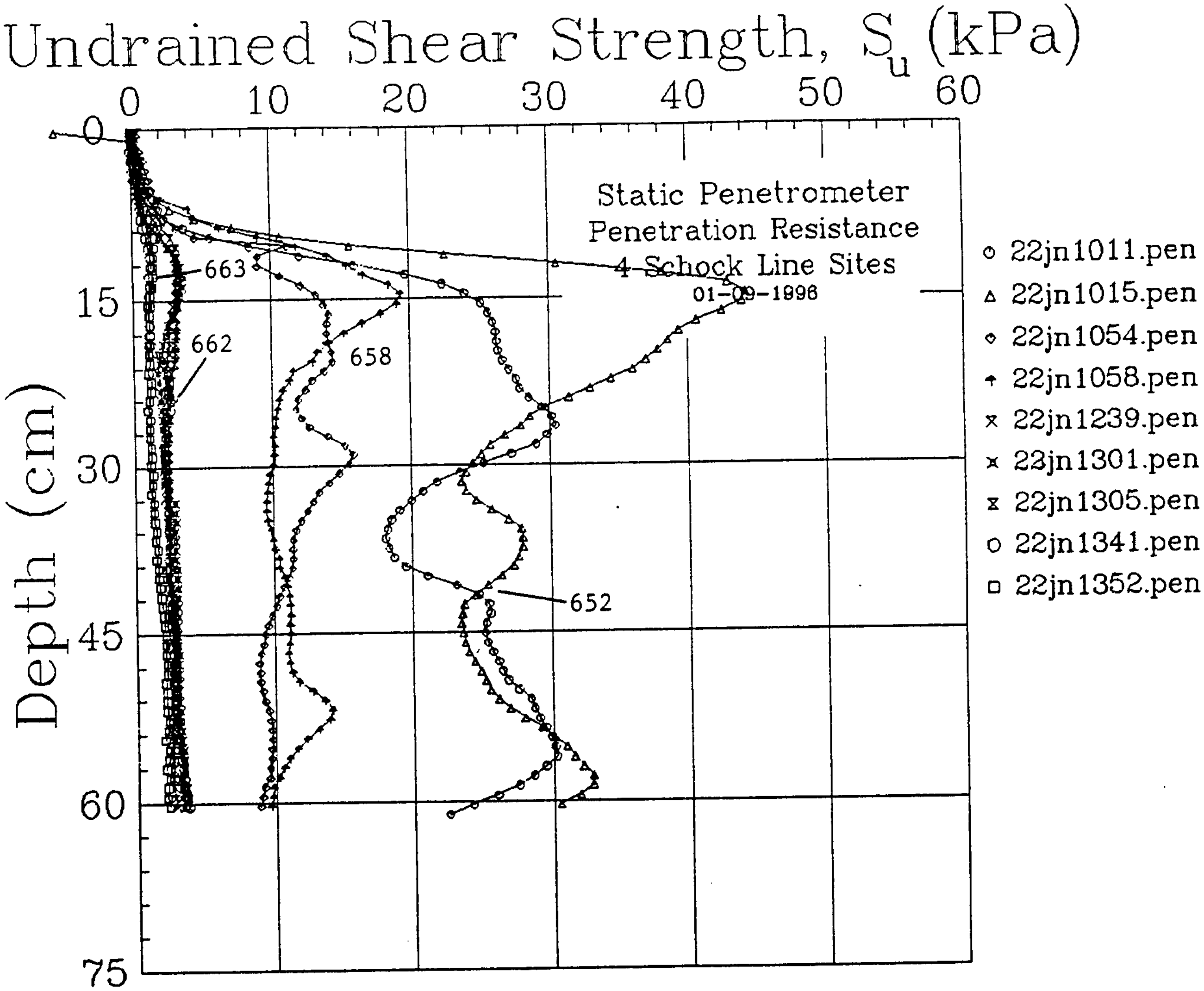

Fig. 2. Undrained shear strength determined from quasistatic cone penctrometer tests at 4 sites along the "Schock" line.

APPENDIX I

LDEO Contibution to Eckernforde Workshop

MEASURING NEAR-BOTTOM SHEAR WAVE VELOCITY USING LOVE WAVES

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ABSTRACT

Love waves are horizontally polarized surface waves that result from multiple reflections in a vertically inhomogeneous medium and since their dispersion is completely controlled by the profile of shear-wave velocities in the medium, they may be analyzed to determine a geoacoustic model of the sediment. Moreover, the use of Love waves instead of the more commonly used Scholte waves, which involve both vertically polarized shear and dilatational motion, offers certain distinct advantages when inversion of the field data is attempted. In particular, the fundamental mode is generally less contaminated by overlap of higher modes and multiple arrivals and hence it is easier to obtain a "clean" dispersion curve which greatly facilitates the inversion process.

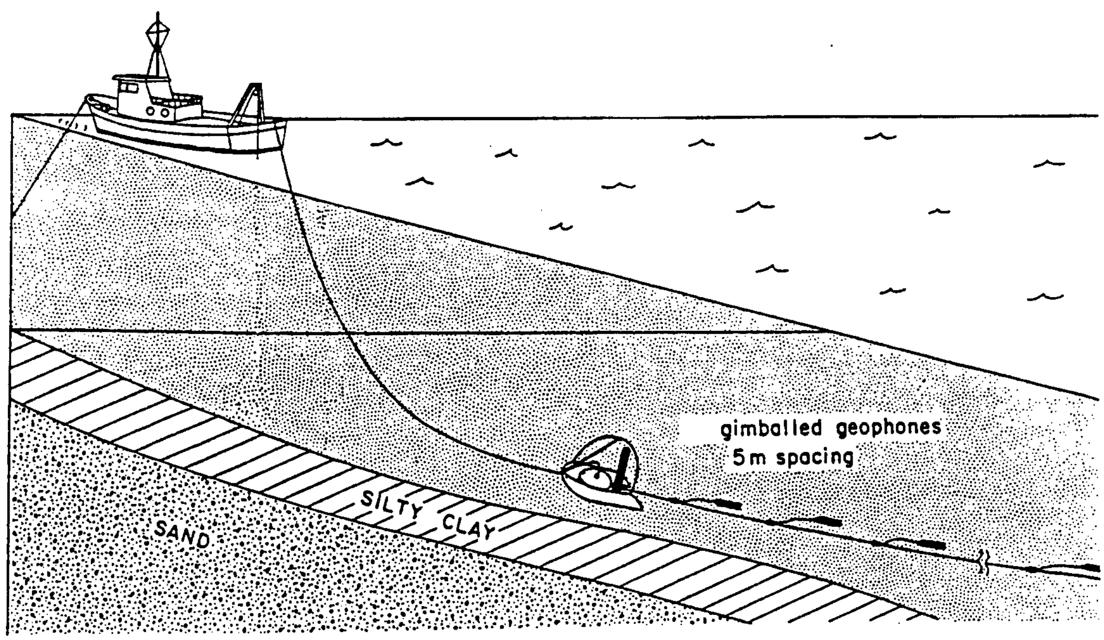

Fig. 1. Field test configuration

In our method of analysis, group and phase velocity dispersion curves are determined from field data and then a least-squares mathematical inversion utilizing singular value decomposition is used to find a sediment model. The test configuration employed to obtain the experimental data used in the analysis is shown in Fig. 1. A torsional source mounted on a self-righting sled is attached to a linear array of horizontally gimballed geophones spaced at five meter intervals along a cable. The sled and cable are lowered and dragged behind the ship for some distance to ensure a uniform, straight geophone array and then the torsional source, which is described in detail in Stoll, Bautista and Flood (1994), applies a torsional pulse to a small circular area of the seafloor using energy supplied by a rotating flywheel that is suddenly stopped. The resulting torque is transmitted to the seafloor via fins that are attached to the bottom of a baseplate in contact with the sediment. A set of seismograms produced by this source is shown in Fig. 2. This data set was obtained in the area of soft, fine-grained sediments in Eckernforde bay during the CBBL experiments in May 1993 and it is unique in the sense that the velocity of shear wave propagation derived from this data is the lowest we have measured in any of our experiments involving near-bottom sediments.

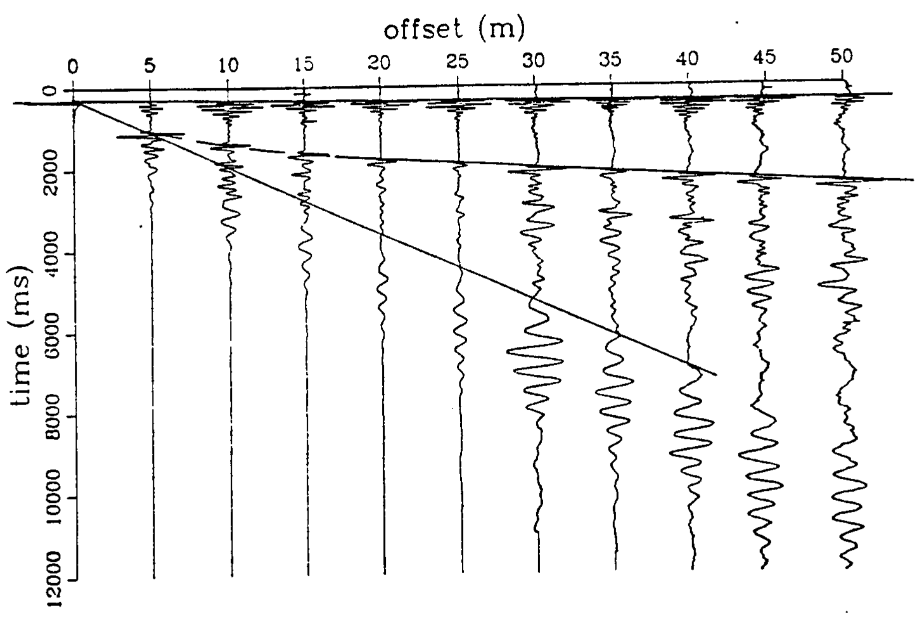

Fig. 2. Seismograms generated by torsional source. Very soft bottom in Eckernforde, Germany. Each trace has been normalized by the maximum signal amplitude so that relative amplitudes of the waves are not comparable.

The first step in the analysis is to generate either group or phase velocity dispersion curves for that portion of the data that is judged to represent the signal produced by a single

mode of Love wave propagation. Group velocity dispersion may be determined from a single seismogram trace of known distance from the source by using the multiple filter technique of Dziewonski, Bloch and Landisman (1969) which generates a contour diagram (Gabor diagram) of the instantaneous amplitude of a complex signal generated by narrow band filtering of the real signal at many different frequencies. Phase velocity dispersion may be determined by generating the cross spectrum for corresponding segments of seismograms obtained from two adjacent geophones. Other methods are also available for determining either group or phase velocity dispersion.

In order to derive a geoacoustic model from experimentally determined group or phase velocity dispersion, it is necessary to establish a theoretical relationship between wave motion observed at the seafloor (i. e., the experimentally determined dispersion curve) and the shear-wave velocity as a function of depth in the sediment column. To accomplish this, an Eigenvalue problem is solved and a periodic equation is derived that defines the permissible modes of propagation in a vertically inhomogeneous sediment column. In order to derive the characteristic equation with roots that define the different modes, one must integrate the equations of motion and apply boundary conditions at the seafloor that eliminate any tangential tractions. The integration can be performed using the Thomson-Haskell method which approximates the vertical inhomogeneity by dividing the soil into many thin homogeneous horizontal layers, or alternatively, the Runge-Kutta method may be used to perform the integration for a smoothly varying velocity-depth model.

As an example, Fig. 3 shows portions of the group and phase velocity dispersion curves calculated by the Thomson-Haskell method for the sediment model shown in the upper right panel of the figure. In this figure the symbols are from the theoretical calculations and the solid and dashed lines are dispersion curves determined from experimental data. Fig. 4 shows the calculated group and phase velocity dispersion for the first three modes of Love wave propagation for the same model. The connection between the model and the theoretical dispersion curves constitutes the "forward" problem, however we are interested in trying to estimate the most appropriate model given the experimental dispersion curves and so must solve the "inverse" problem. In order to find the model that yields dispersion curves with the best a match to the experimental data, an iterative solution that requires repetitive solution of the forward problem is used. Because the inverse problem is nonlinear and basically "ill posed" and the solutions are obtained in the least squares sense, considerable care is necessary in order to avoid unrealistic solutions that represent local minima. A more complete discussion of inversion procedures is given in Bautista and Stoll (1995).

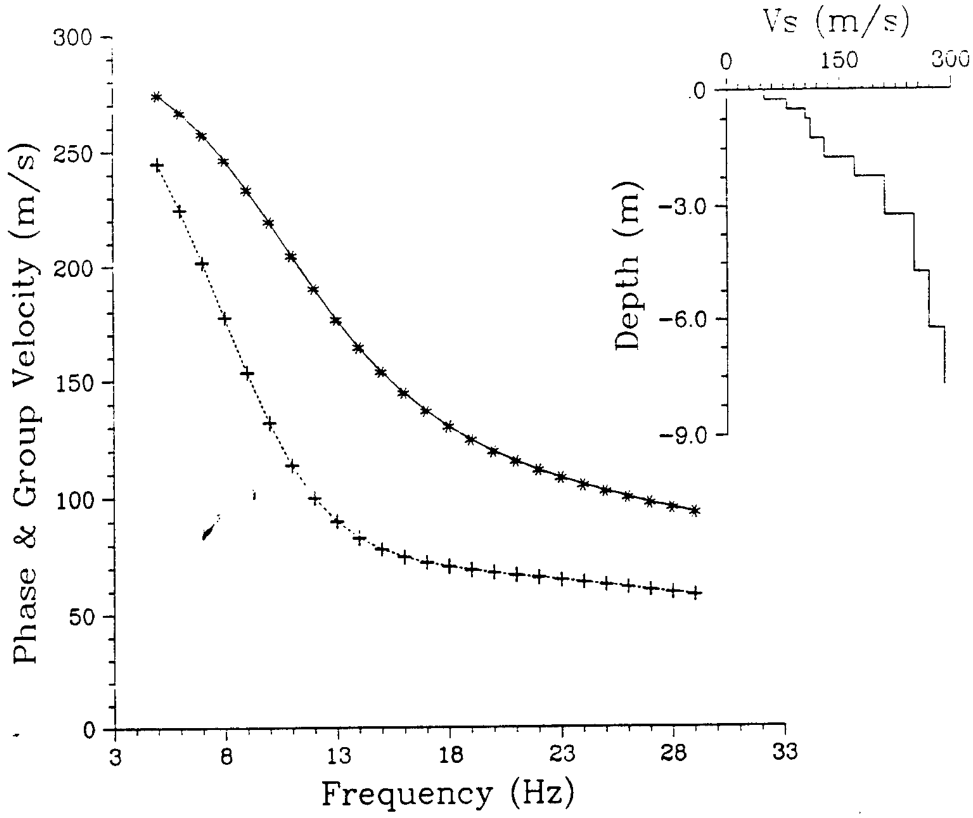

Fig. 3. Model for sand bottom and corresponding group (+) and phase (*) velocities

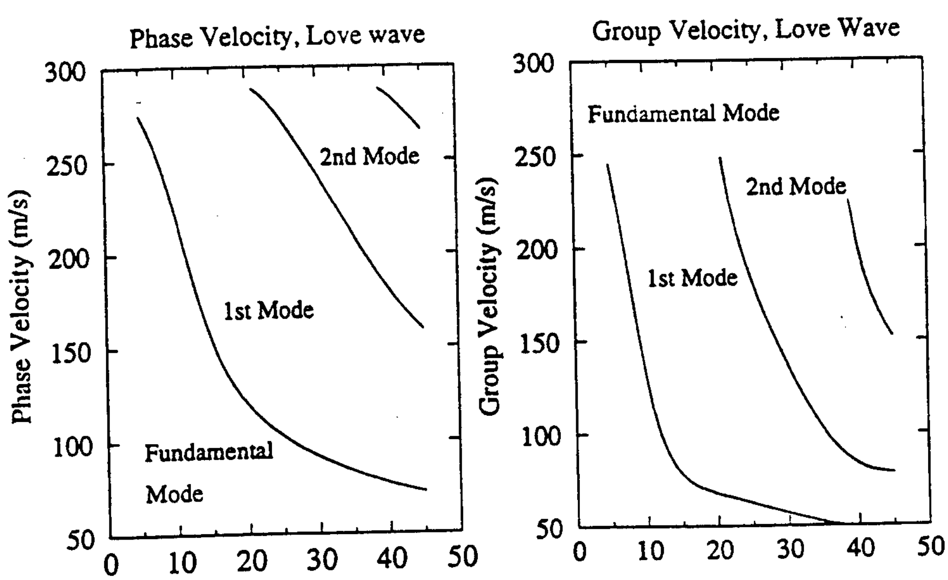

Fig. 4. Group and phase velocity for first three modes. Same model as in Fig. 3.

Fig. 5 shows the dispersion curves and model derived for channel 8 of the data shown in Fig. 2. The shear-wave velocity of about 5 m/s at the seafloor is the lowest we have recorded in our field work to date. Moreover, the rather rapid increase in shear-wave velocity with depth is consistent with the refracted shear arrivals and wavelets corresponding to higher modes that precede the fundamental mode in the seismograms of Fig. 2.

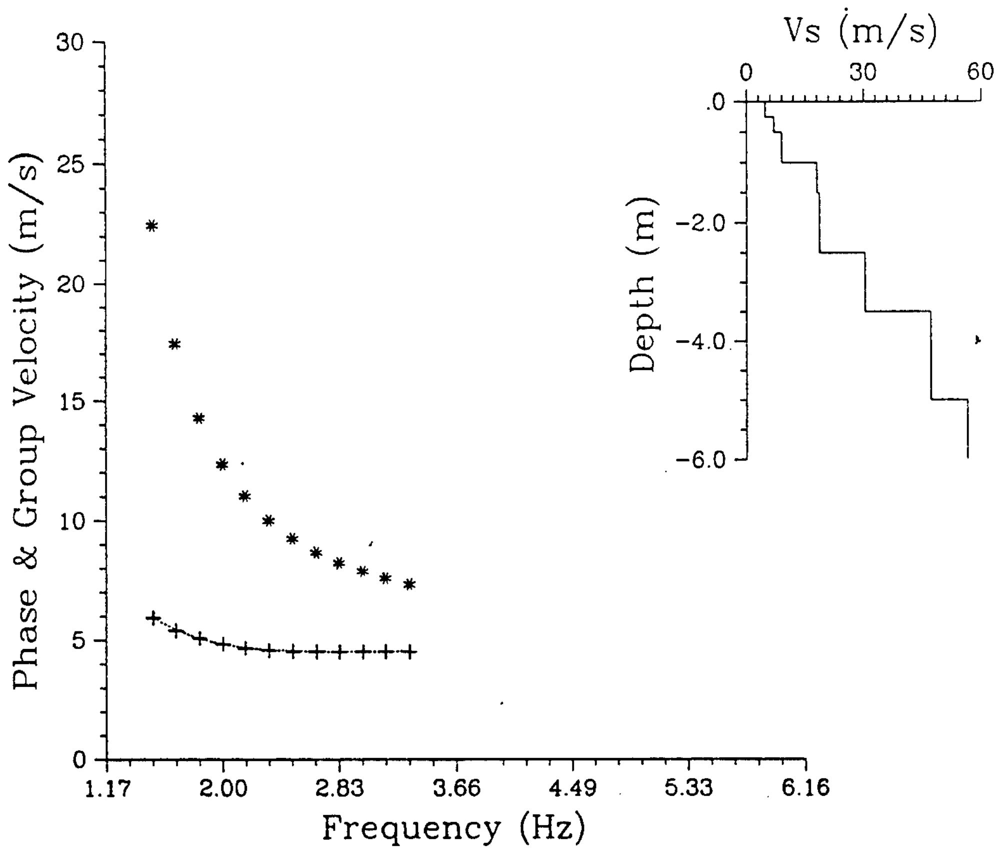

Fig. 5. Model and dispersion curves derived for data of channel 8 in Fig. 2.

In general, we have found the use of Love waves to be very advantageous in studies of near-bottom velocity structure because the dispersion curves for Love waves tend to be less affected by refractions and interference between modes than in the case of Scholte waves.

Work supported by CBBLSRP and ONR.

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2.17 Characterization of Surfacial Roughness and Sub-Bottom Inhomogeneities from Seismic Data Analysis (Principal Investigators: D.J. Tang and G.V. Frisk)

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Objectives

During the first two years of the Coastal Benthic Boundary Layer Special Research Program, three major experiments have been successfully conducted. The data sets obtained in the experiments provided acousticians with the opportunity to comprehensively study problems related to high-frequency acoustics scattering from various shallow water sediments. Geoacoustic data measured in situ and in the laboratories are of critical importance to be used as input in acoustic scattering models. Our objectives in this program are integrating various acoustic data with available environmental data, modeling the scattering processes in shallow water sediments. Our work completed in 1995 is a continuation of our efforts in the past two years. The emphasis is placed on the analysis and modeling of scattering by gassy sediments.

Accomplishments

During the past year, our primary work has been in the areas of developing a theory of high-frequency acoustic scattering from gassy sediments. One of the experiments sponsored by the Coastal Benthic Boundary Layer Program (CBBL) was conducted in Bay, Baltic Sea. This site features soft sediments where the sound speed in the top layer of sediment is slower than that in the water column near the bottom. For a detailed description of this experiment, please see Richardson (1994). In a previous paper (Tang et al. 1994), analysis of high-frequency (40 kHz) small grazing angle (5-20 degrees) acoustic backscattering data collected from Eckernförde Bay suggests that a layer of scatterers are buried about a meter beneath the seafloor. These scatterers, treated as an equivalent surface scattering layer, have a relatively large backscattering strength of -10.8 dB. Coring and X-ray tomography analysis (Abegg et al. 1994) reveal methane gas voids of non-spherical shapes, which are clearly the dominate scatterers in this site. Usually, at small grazing angles, high-frequency acoustic waves are highly attenuated before reaching buried scatterers because the ray path traversed in the sediment is long. At Eckernförde Bay, however, the combination of low attenuation and a slower bottom sound speed compared with that in the water column (Tang et al. 1994, Richardson and Briggs 1996) makes the scattering from the deeply buried gas voids measurable. It is interesting to notice that the estimated backscattering strength of -10.8 dB is several decibels higher than that at a sandy site off Panama City, FL (Tang et al. 1994) where bottom interface scattering is dominant. In order to understand the scattering mechanism, we modeled the acoustic backscattering by non-spherical gas voids from Eckernförde Bay based on models of scattering by non-resonant oblate spheroids at various aspect ratios. Available geological parameters obtained in the field by other investigators were used in the model/data comparison. Although this model does not take into account the exact geometrical shape of the gas voids, it should capture the facet scattering nature common to

scatterers with sizes comparable to wavelength. It was found that the averaged backscattering strength of an oblate spheroid has little angular dependence, as is the case found in measured scattering data. The scattering strength vs. grazing angle matched the measured data, and the average number of gas voids needed to match the measured backscattering strength was in reasonable agreement with measured bubble distributions in a core. The results were given in a paper to be published in a special issue of Geo-Marine Letters. Because of the complexity of the problem and the limited supporting data, this paper is not intended to obtain conclusive results, but rather provides a possible scattering mechanism to account for the acoustic backscattering measurement at 40 kHz in Eckernförde Bay. Other possible models, such as multiple scattering and resonant scattering models, should be studied in the future. In our modeling, the oblate spheroids are configured as standing on their edges to approximate the configuration of gas voids found in the cores. As a result, the model will predict larger scattering strengths at small grazing angles. In another paper, which is a collaboration with Chu of WHOI, and Williams and Jackson from University of Washington, the same model is extended to include bi-static scattering geometry. In that study, we used the same parameters determined in the backscattering analysis, and we found the model-data comparison is satisfactory for the bi-static scattering data collected by Williams and Jackson. Partial results were presented in the Workshop, ``Modeling Methane-Rich Sediments of Eckernförde Bay June 26-30 (1995)."

Preliminary Conclusions and Relevance to CBBL Objectives:

One major goal of the CBBL program is to provide integrated models of shallow water sediments. Our efforts help in the area of modeling acoustic scattering by gassy sediments. It is easy to conclude that when gas bubbles are present, they are a major, often dominant, scatterers of acoustic waves. It is, however, much more difficult to conclude what kind of scattering mechanism controls the scattering process. While understanding that resonant scattering and multiple scattering by gas bubbles are possible, we have extensively studied the scenario of facet scattering mechanism at high frequency (40 kHz). We conclude that it is definitely possible that facet scattering is the main scattering mechanism at high frequency (40 kHz). In the next two years, we intend to continue our efforts to integrate other available acoustic data obtained in the gassy sediments to examine the frequency and spatial dependence of scattered wave to gas distributions. Meanwhile, we will start study scattering problems related to the data collected in the sandy and carbonated sediments.

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Chu, K. L. Williams, D. Tang, and D. R. Jackson, ``Modeling of bi-static scattering from sediment bubbles," to be submitted to the J. Acoust. Soc. Am.

D. Tang, ``A note on scattering by a stack of rough interfaces," Accepted by J. Acoust. Soc. Am.

2.18 Observation of Bottom Boundary Layer Hydrodynamics and Sediment Dynamics in Eckernförde Bucht and the Gulf of Mexico off Panama City, Florida (Principal Investigators: L.D.Wright and C.T. Friedrichs)

L.D. Wright and C.T. Friedrichs

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1. Summary of Work During the Period:

Effort in FY 1995 was focused on: (1) execution of the field experiment off Key West and maintenance of field equipment used throughout CBBL/SRP, (2) analysis and interpretation of this field data as well as further interpretation of data collected previously in Eckernförde Bay; (3) further development of conceptual and mathematical models for explaining our observations; and (4) preparation of conference presentations as well as preparation and publication of journal articles reporting our results.

2. Objectives:

The overall objective of this ongoing study continues to be elucidation of temporal and spatial variability of the processes that form, modify and preserve sedimentary strata in a variety of shelf settings. In the specific case of the VIMS component of the larger multi-institutional effort, we have been addressing questions related to: (1) hydrodynamic forcings (benthic physical oceanography); (2) bed stress measurement, including the impact of near-bottom density stratification; (3) bed micromorphodynamics and roughness variations; (4) sediment resuspension; and (5) sediment flux divergence and bed level changes.

3. Eckernförde Bay:

3.1. Accomplishments:

Analyses, interpretations and dissemination of our results from Eckernförde Bay progressed rapidly over the last year. Two presentations on the physical oceanography of the bay and its relation to bottom stress, sediment resuspension and sediment transport were given at the Workshop Modelling Methane-Rich Sediments of Eckernförde Bay, held in Eckernförde in June. A paper on the subject of one talks just appeared in a recent issue of Continental Shelf Research, while the second has been submitted to the Journal of Geophysical Research. (Ten reprints of the CSR article are enclosed here, along with a single copy of the JGR manuscript.) Wright was also a co-author of a talk at the Eckernförde Workshop presented by C. Nittrouer on the subject of sedimentary character and its relationship to environmental processes. We are also in the process of collaborating on a paper with M. Jackson, K. Williams and T. Wever on the subject of

acoustic observation of methane ebullition for the upcoming Continental Shelf Research special issue on Modelling Methane-Rich Sediments of Eckernförde Bay.

3.2. Major Conclusions:

(1) The physical oceanography of Eckernförde Bay in April and May of 1993 appears to be dominated by a resonant internal seich forced, in turn, by a Baltic-wide barotropic seich.

(2) A simple two-layer analytic model explains the generation of these internal waves and accounts for velocities much larger than those otherwise predicted by barotropic processes.

(3) Turbidity events are associated this ~26-28 hour internal seich, but probably indicate advection of unconsolidated sediment flocs rather than local resuspension of the consolidated bed.

(4) Currents produced by the internal waves are sufficient to advect fine sediment into the bay, but internal wave breaking may limit stress levels to below that required for resuspension.

(5) Eckernförde Bay also provides a natural laboratory for investigating the sensitivity of bottom stress and roughness measurements to density stratification and instrument settling.

(6) In central Eckernförde Bay, stratification and settling causes "overshooting" of the classic logarithmic velocity profile, leading to a potential ten-fold overestimate of bottom stress.

(7) Theoretical corrections successfully improve curve-fits and reduce estimates of stress and roughness to below the unreasonably high values predicted by simple log-profiles.

3.3. Significance to CBBL objectives:

Our observations from the center portion of Eckernförde Bay suggest that bottom stress levels are commonly sufficient to advect fine sediment into the bay, but are not sufficient to cause local resuspension. These conclusions, based on a study of the physical oceanography and structure of the bottom boundary layer, are highly consistent with complementary studies of stratigraphic development in the central bay performed by CBBL/SRP investigators from SUNY and elsewhere. Complementary studies led by C. Nittrouer, for example, found rapid rates of sediment accumulation and minimal physical mixing of surficial sediment. Generation of currents by internal wave resonance, in concert with the presumed gradient in near-bottom storm wave activity from shallow to deeper water, together provide a reasonable scenario for rapid, but quiescent accumulation of mud in the central bay. The rapid accumulation of mud with little physical mixing is, in turn, highly consistent with the ultimate generation of Methane-Rich sedimentary strata.

4. Key West

4.1. Accomplishments:

An instrumented bottom boundary layer tetrapod was deployed from the R/V Pelican on the Dry Tortugas Bank at a depth of 26 m on 4 February 1995 and retrieved on 25 February 1995. The tetrapod supported the same suite of instruments as used in the Eckernförde and Panama City campaigns. Included were a deep sea camera, five electromagnetic current meters, a pressure sensor, five optical backscatterance sensors, and a sonar altimeter. Although the camera and one of the current meters failed, the deployment was otherwise quite successful and yielded a full set of good quality data. The absence of photographs from the tetrapod was partially made up by video imagery acquired by divers, as illustrated by Figures 1-3.

4.2. Preliminary Conclusions:

(1) Burst-averaged pressure and velocity records were mostly tidal, with tides accounting for 93% and 66% of the total burst-averaged pressure and velocity variance, respectively.

(2) Burst-averaged velocity was 20 cm/s or less, except during the wind event at the start of the deployment when speeds reached 35 cm/s. The wave orbital amplitude was small (< 10 cm/s).

(3) A 5 cm thick fluff layer mantled the bottom following the wind event and may have been deposited during the waning phase of the storm (Fig. 1).

(4) Three weeks later, the fluff was gone, revealing a biologically-roughened bed (Fig. 2). Sediments were apparently bound by an algal crust just below the sediment/water interface.

(5) Velocity profiles suggest that throughout the deployment the bed was hydraulically very smooth despite the presence of biogenic roughness elements after the removal of fluff.

(6) During the early phase of the deployment, a swath was cut through the algal crust by a mooring anchor that was dragged past the tetrapod. This allowed the underlying sediment to respond to the physical flow regime by developing a train of regular, sharp crested ripples (Fig. 3).

(7) Thus flows would have generated ripples in the absence of the algal crust, but the crust inhibited response of the bed to physical processes, allowing biological roughness to dominate.

4.3. Significance to CBBL objectives:

A general goal of the Key West Campaign was to gain better understanding of the effects that biogeochemical processes have on the behavior of surficial sediments and associated geoacoustic properties in carbonate sedimentary environments. More specifically, the VIMS bottom boundary layer hydrodynamics and sediment transport experiments provided essential environmental information on the physical regime, hydraulic roughness, and the factors that affect sediment mobilization and mixing of the sediment column.

5. Publications and Presentations to Date:

5.1. Journal Articles:

Friedrichs, C.T., and L.D. Wright, 1995. Resonant internal waves and their role in transport and accumulation of fine sediment in Eckernförde Bay, Baltic Sea. Continental Shelf Research, 15: 1697-1721.

Friedrichs, C.T., and L.D. Wright, submitted. Sensitivity of bottom stress and bottom roughness estimates to density stratification and instrument settling, Eckernförde Bay, Southern Baltic Sea. Journal of Geophysical Research.

5.2. Presentations:

Friedrichs, C.T., L.D. Wright, and B.-O. Kim, 1995. Sensitivity of bottom stress measurements to stratification, fluid acceleration and instrument settling, Eckernförde Bay, southern Baltic Sea. Proceedings of the Workshop Modelling Methane-Rich Sediments of Eckernförde Bay, Eckernförde, Germany, 26-30 June, 1995, pp. 140-144.

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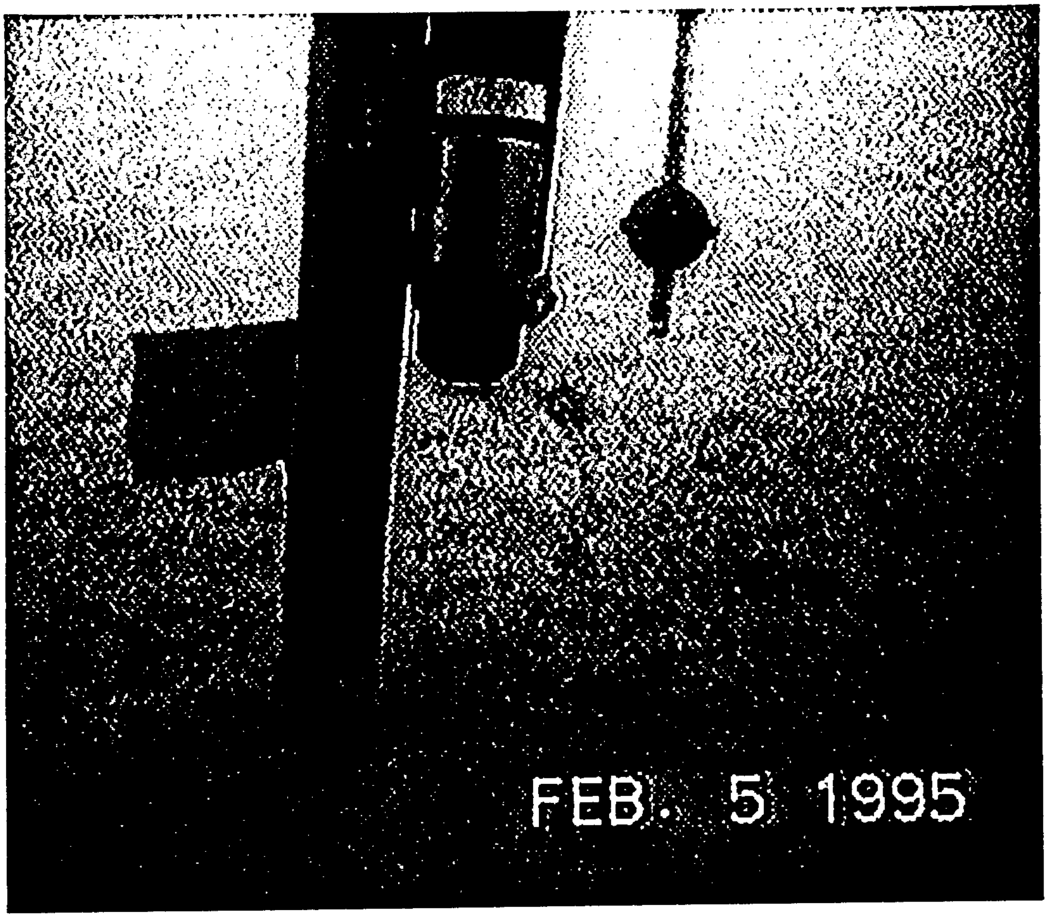

Figure 1. A 5 cm thick fluff layer was found to mantle the bottom soon after the wind event which occurred at the start of the deployment. In the foreground is an optical backscatterance sensor and a scale marked in inches which has been pushed down through the fluff by a diver. In the background is an electro-magnetic current meter.

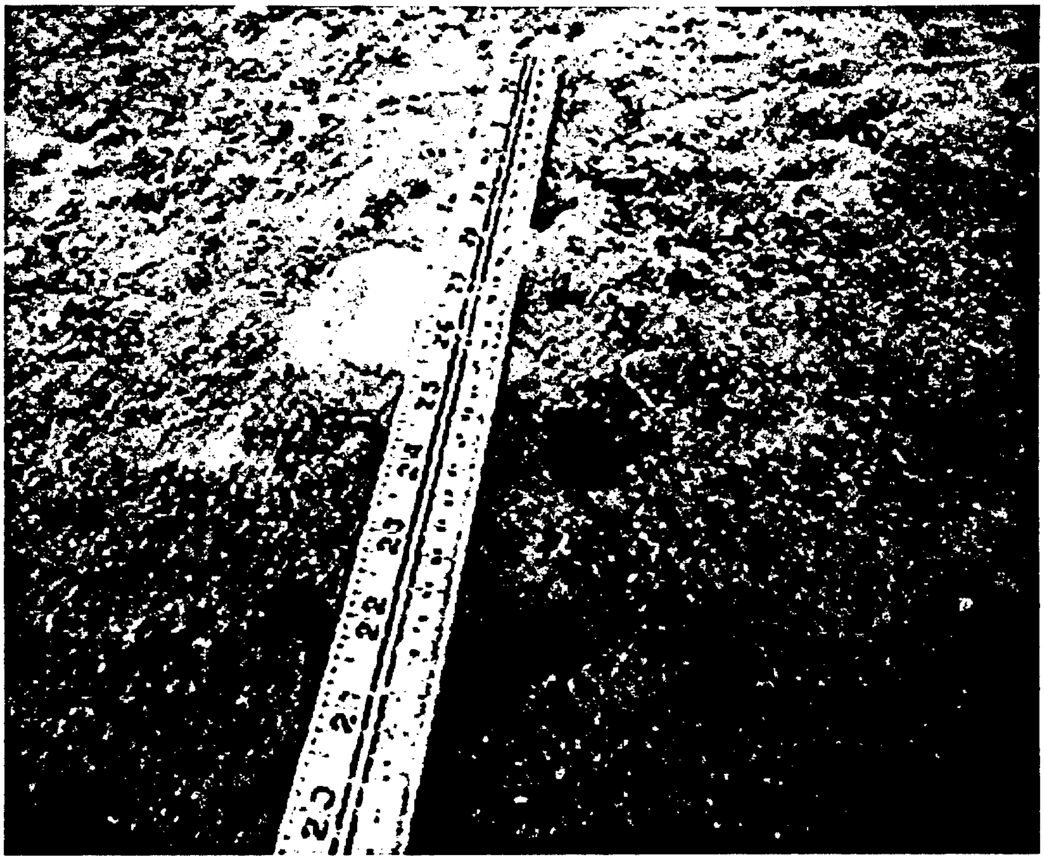

Figure 2. At the end of the deployment the bottom was biologically-roughened by shrimp burrows, and the surface layer of sediment was apparently bound by an algal crust. The scale is marked in inches and centimeters.

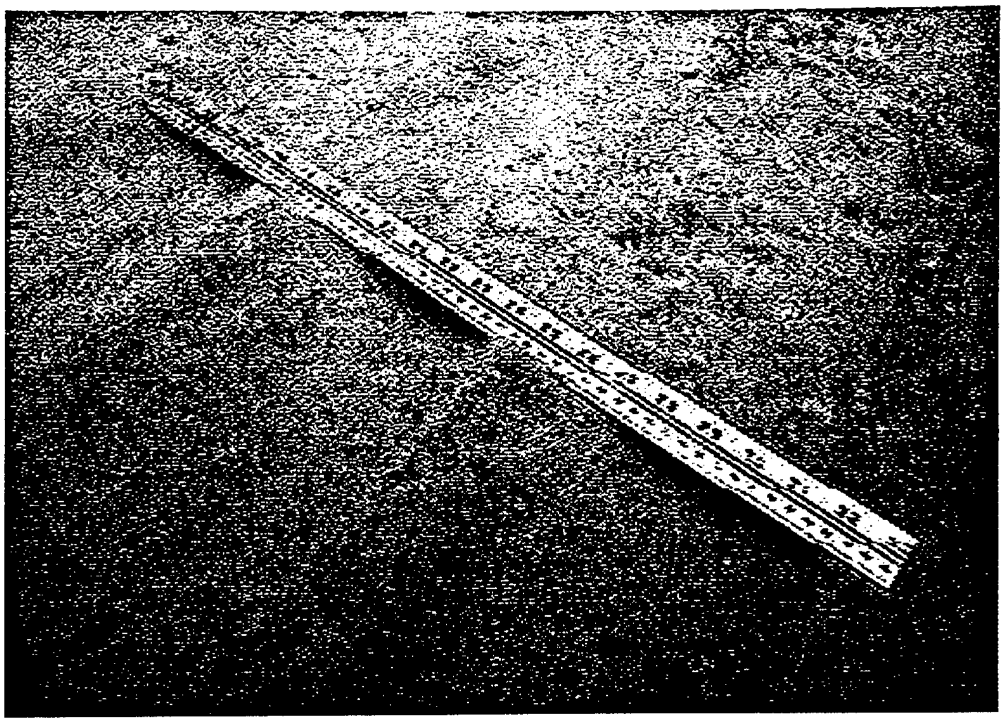

Figure 3. A train of sharp, regular crested ripples formed after a swath was cut through the algal crust by a mooring anchor that was dragged past the tetrapod. The scale perpendicular to the ripple crests is marked in inches and centimeters.

2.19 Image Analysis of Sediment Texture (Principal Investigators: D.K. Young, R.J. Holyer and J.C. Sandidge)

CBBL FY95 Year-End Report for Image Textural Analysis Project

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The long term goal of our investigations is to derive new sediment textural classification methodologies based on image analysis and to use resulting variables directly as predictive model inputs or as proxy measures of and predictors for acoustic and physical properties of marine sediments. These image-based textural parameters are, by their very nature, readily automated for highly discriminating, rapid and reproducible results. As suggested from other applications of imaging science, these parameters could be particularly useful in quantifying inhomogeneities of sediment fabric patterns, including sediment contrast boundaries, gradients, interfaces, and anisotropy of component features. As a first step toward this goal, we have identified a number of potentially useful image analytical approaches to quantify sediment texture (Young *et al.*, 1994) and have demonstrated relationships between image-based measurements and sediment bulk density (Holyer *et al.*, 1995). In the study recently submitted for publication (Holyer *et al.*, submitted), we use two image texture analytical techniques to quantify the scales, orientation, and isotropy of density fluctuations imaged in cross-sectional X-radiographs of marine sediments.

Summmary of Image Processing Work: Four Eckernförde Bay x-radiographs forming a set of observations along the "Schock" line and a fifth at the NRL acoustic tower site were the subjects of the analysis of density structure of Eckernförde Bay sediments. The working hypothesis for analysis of these x-radiographs was that film transparency is proportional to bulk gravimetric density. Table I gives coordinates of the stations.

TABLE 1: STATION LOCATIONS

STATION	LATITUDE	LONGITUDE	WATER DEPTH
634	54°29'89.8"N	10°00'10.9"E	25m
652	54°31'05.6"N	10°07'37.6"E	18m
658	54°31'01.0"N	10°07'18.5"E	19m
662	54°30'50.6"N	10°06'31.1"E	30m
663	54°30'15.5"N	10°06'05.1"E	20m

Stations from the Schock line, running from Stollergrunde to Mittelgrund, are stations 652 and 658 comprising fine sand, and stations 662 and 663 which are mud. The bulk properties for station 634 are previously given in several CBBL documents (Briggs and Richardson, 1994). Data from only stations 634 and 662 are discussed here. Results for all five were presented at the June workshop (Holyer *et al.*, 1995). The methodology for producing the x-radiographs of sediment cores is as previously described by Holyer, *et al.* (submitted). The approach to the analysis of these x-radiographs is three-fold. First, demonstrate and quantify a relationship between image transparency and bulk density, *i.e.*, experimentally justify the working hypothesis stated above. Second, compare the bulk and image-based observations of density structure and demonstrate the types of sediment information that can be retrieved from each. Third, relate density information derived in this manner with knowledge of these sediments gained by other means, i.e., tie these results into the overall CBBL project objectives and results.

Figure 1 is a plot of the film transparency vs. bulk density for each of the x-radiographs. The film transparency values in Fig. 1 are averages over horizontal strips 2 cm high and extending the width of the image. Bulk density was measured by conventional techniques at 2 cm intervals along a core extracted from the same box core as the x-radiograph core (Briggs and Richardson, 1994). Bulk density values for a given distance below the water-sediment interface were paired with the film transparency strip averages from the same depth into the sediment. These paired values are indicated by the symbols in Fig. 1. For each of the four sets of points, a linear least-squares fit was calculated and plotted as a dashed line in Fig. 1. The coefficients of the linear relationship are not universal because of the uncalibrated nature of the data acquisition. However, the linear fits here do allow conversion of digital counts in the images to bulk densities for these five x-radiographs.

When x-radiograph film transmittance is calibrated in units of bulk density, the imagery provides high resolution vertical profiles of density showing more detail of the density structure than is observable from traditional bulk measurements. Furthermore, since vertical profiles can be generated easily, it is possible to produce many profiles taken from various positions within the sample to display and quantify horizontal variability of the sediment density distribution. Adequate numbers of vertical profiles to estimate horizontal variability of a core are seldom taken with traditional methods because of the laborious nature of the procedure. Figure 2 shows high resolution image-based density profiles for sample 634. The figure also shows the mean profile and standard deviation of the density profiles as a function of depth. This example is a featureless profile showing a monotonically increasing value of density with depth. However, the standard deviation of the horizontal fluctuations of density is not uniform. The figure shows a band of increased variability from between 4 and 8 cm depths. This near surface band of increased variability may be evidence of sediment lamenations resulting from storm events (Bentley, *et al.*, submitted).

Figure 3 presents the same density profile information for sample 662. In this sample there is distinct density stratification. The overall density variability is also much higher than in sample 634. The important message from Figs. 2 and 3 is that the x-radiograph gives much more information on sediment density structure than does the conventional bulk method. Parameterizations of density structure from high resolution profiles (density variance, vertical gradient of density, etc.) may provide useful inputs to geoacoustic models.

Characteristic length scales in sediment density structure can be quantified from the x-radiograph image autocorrelation function. The normalized autocorrelation function, $\phi(x,y)$, of image $I(s,l)$, is given by

$$\Phi(x,y) = \frac{1}{\sum_s \sum_l I^2(s,l)} \sum_s \sum_l I(s,l) I(s-x,l-y) \tag{1}$$

where, s and l are sample and line numbers within the image, respectively, and x and y are correlation "lag" or offset values. In other words, the autocorrelation function has, by definition, a value of 1 when $x=y=0$. For nonzero x,y offsets, the autocorrelation function assumes values ranging from -1 to 1. The rate of decline in the correlation value with size of the offset gives a correlation length indicating dominant spatial scales in the image gray-tone features. Correlation length, L, is defined as the x,y offset length at which the correlation value has dropped to $1/e$ (e=2.7183). Yaglom (1987) gives a formula for calculating correlation length of a data sequence,

$$L = \left[\frac{1}{2} + \frac{\Phi(x)}{1-\Phi(x)}\right] x \tag{2}$$

where, $\phi(x)$ is the value of the autocorrelation function at offset x. Equation 2 is based on assumption that correlation decreases with lag according to the exponential function $\exp(-x/L)$. This assumption is not always valid, so correlation lengths calculated from the formula are subject to error. In our image-based representation of sediment density, we calculated $\phi(x,y)$ and presented the result in an image format. That is the autocorrelation function of the x-radiograph is displayed as an image where correlation values are encoded as gray levels. Correlation lengths have also been calculated for all values of x (horizontal correlation length) and all values of y (vertical correlation length).

Figure 4 shows the x-radiographs for stations 634 and 662. For each x-radiograph, its autocorrelation function is displayed to the upper left. Calculated horizontal and vertical correlation lengths (Eq. (2)) are plotted as a function of sample interval to the lower left. The solid white bar in the lower left corner of each x-radiograph represents 5 cm. The autocorrelation function is displayed at the same scale as the image.

Observe that in both cases, the horizontal correlation length is significantly larger than the vertical correlation length. This observation is expected for stratified density structure. Bulk measurements of density along a vertical core give only the vertical correlation length which is in error if it is assumed to apply in both directions. The ratio of horizontal to vertical correlation lengths provides a quantification of the anisotropy of the density structure, a useful parameter for acoustic modeling. The correlation length plots show that calculated correlation length is a function of sampling interval. Correlation length based on 2 cm sampling along a core can be very different than values based on 1 cm or 4 cm sampling. One can get almost any correlation length desired by choosing the appropriate sample interval. To intercompare results among investigators, sample intervals should be standardized. Perhaps correlation length should be abandonded completely since it is based on exponential decay of correlation with distance. This exponential decay does not occur in stratified structure. The problems that result from making this assumption when it is inappropriate are demonstrated in the correlation length plots for sample 662 where vertical correlation length goes negative for sample intervals above 4.5 cm. A negative correlation length is a physical impossibility, this result follows directly from the erronous assumption.

This summarization comparing bulk density with x-radiograph image transparency at cm scales is an example of our approach. We are also comparing other image-based analyses to other bulk properties. Particle size distribution will be compared with image analysis results from TEM images and thin-section photomicrographs. Preliminary results of the analysis at these other scales will be presented at the workshop on Sediment Geoacoustical and Geotechnical Constitutive Modeling held at the University of Rhode Island, 13-14 November, 1995.

<u>Summary of Field Work</u>: We have used a diver-operated sediment profile camera to document organism-sediment relations and to gain in situ information about sediment texture by obtaining high resolution photographs of the sediment-water interface. X-radiographs of box-core sediments have been obtained (cooperatively with Kevin Briggs) from a variety of benthic environments in the 1993 and 1994 Eckernförder Bay experiments. Measurements of geoacoustics and sediment properties were collected by other CBBL scientists. All x-radiograph samples were photographed to document down-core changes of color and texture. Some of these x-radiographs allowed subsampling from specified locations within the cores (via one side being removable) for collection of samples for thin-sectioning and electron microscopical analysis of microfabric (cooperatively with Dennis Lavoie) and for grain size and index property analyses (cooperatively with Dawn Lavoie). Our analyses of imagery of these samples will permit us to compare differences from known sample locations and depths with image-based measures of texture from the microfabric scale to the macrostructural scale of variability.

Sediment profile images collected during the Key West Expedition, during February 1995, were taken by two in situ methods- sediment profile photography and x-radiography. SCUBA divers were used in sampling at several sites at the Dry Tortugas experimental area to minimize disturbance of the sediment-water interface and surficial sediments. The

x-radiographic cores used by divers were 36cm wide by 44cm high and 3 cm thick. The cores were stored in a container of sea water before they were photographed and x-radiographed using previously described methods. Subsequent to being imaged, the x-radiographic cores were analyzed by electrical resistivity methods by Peter Jackson and Robert Flint. Several of these cores were subsampled for electron microscopy of microfabric by Dennis Lavoie. Diving could not be done at the Marquesas experimental area because of high sea state so an x-radiograph core was taken from a box core sample there.

Sediment profile photographs were taken also in an acoustic experiment during April-May 1995 at Panama City Beach. These photographs were taken at a site of 10 m water depth which was characterized by a well-sorted fine sand sediment. Analyses of these photographs will provide an opportunity to apply image-based textural approaches to quantify size frequency distributions, porosity and isotropy of sediment structure where hydrodynamic processes are dominant.

Future Plans: Proposed work will emphasize analysis of these data sets and imagery collected during past field experiments. No direct participation in FY96 field experiments is planned with the possible exception of the PLANET cruise in August 1996. X-radiographs (provided cooperatively by Kevin Briggs) will afford us the opportunity to examine and quantify relationships among imaged textural structure and sediment properties and to interpret processes responsible for sediment structure. The x-radiographs collected in FY 96 will be calibrated with an aluminum wedge permitting better quantification of imaged density structure.

With the addition of imagery analyzed in FY96, we will have a rich data base to develop unifying hypotheses for tests of image-based quantification and classification of sediment structure. These tests will form the culmination of our CBBL work and will be the primary focus of our work in FY97. Comparisons of image-based statistical estimates of sediment texture with measured sediment properties from each experimental site will provide a rigorous test of the robustness of the image textural approach. We plan to analyze imagery of sediments over a wide range of size scales in differing sedimentary environments to obtain statistical estimates of measured sediment properties and geoacoustic parameters. We will add fractal geometry to our analyses which may contribute to unifying theories.

Presentations:

Holyer, R. J., D. K. Young, J. C. Chase and K. B. Briggs (1994) Sediment density structure inferred by textural analysis of cross-sectional x-radiographs and electron microscopy images. EOS, Transactions, American Geophysical Union, 75 (3):202.

Young, D. K., R. J. Holyer, and J. C. Sandidge (1994) Texture of sediments from Eckernförde Bay: An image analysis approach. Gassy Mud Workshop, FWG, 11-12 July 1994.

Holyer, R. J., D. K. Young and J. C. Sandidge (1995) Density structure of Eckernförde Bay

sediments derived from image analysis: Relationships with sediment properties. Workshop on Modeling Methane Rich Sediments of Eckernförde Bay, Eckernförde, Germany, 26-30 June 1995.

Publications:

Holyer, R. J., D. K. Young, J. C. Sandidge, and K. B. Briggs (submitted) Sediment density structure derived from textural analysis of cross-sectional x-radiographs. GeoMarine Letters.

References:

Bentley, S.J., C.A. Nittrouer, and C.K. Sommerfield (submitted). Development of sedimentary strata in Eckernförde Bay, southwestern Baltic Sea, GeoMarine Letters.

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Yaglom, A.M. (1987). Correlation Theory of Stationary and Related Random Functions, Volume I: Basic Results, Springer-Verlag, New York, 526 pp.

Figures:

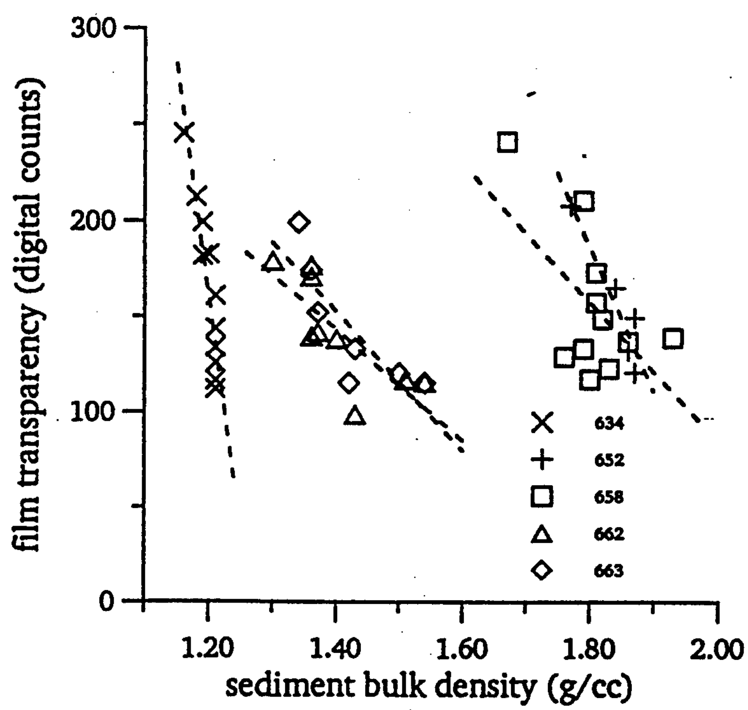

Figure 1: Film transparency vs. sediment bulk density for five x-radiograph stations. A linear least-squares fit from the points for each x-radiograph are shown as dashed lines.

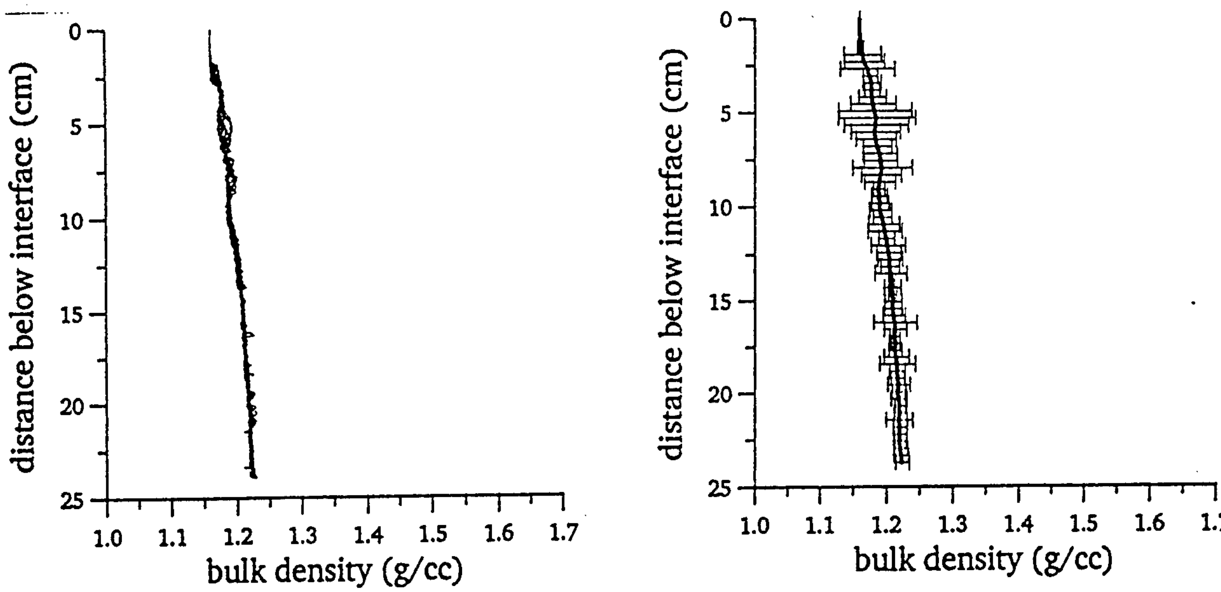

Figure 2: Eight representative density profiles extracted from x-radiograph 634 (left). Mean value of the eight profiles (solid line) and their standard deviation (error bars). Standard deviation bars scaled by 7.0 for improved appearance (right).

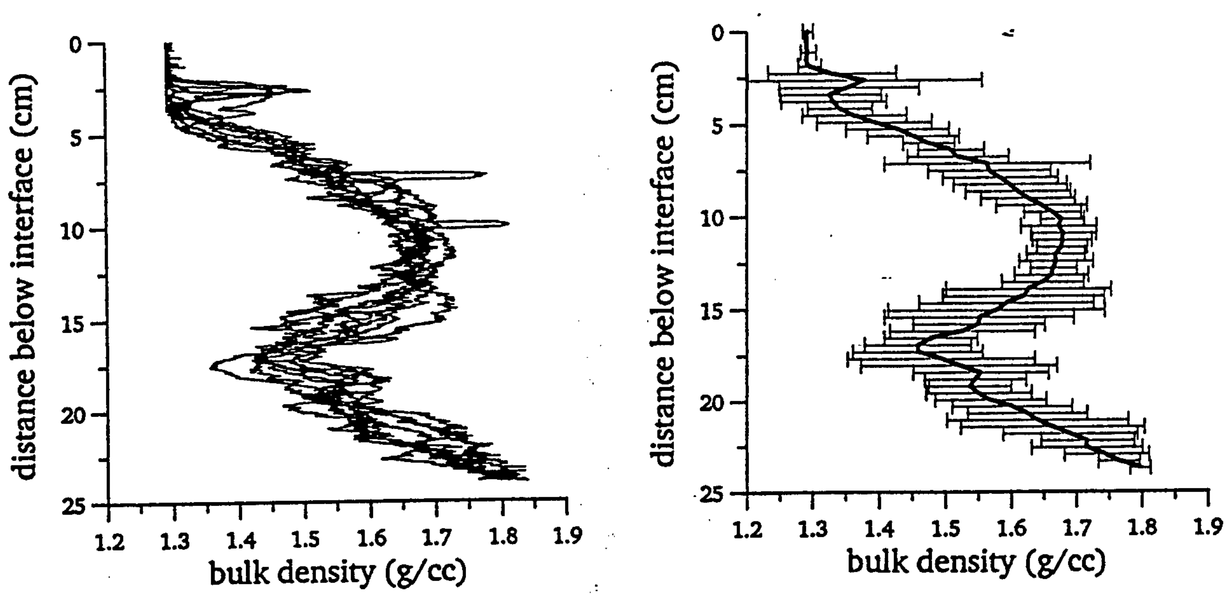

Figure 3 : Eight representative density profiles extracted from x-radiograph 662 (left). Mean value of the eight profiles (solid line) and their standard deviation (error bars). Standard deviation bars scaled by 2.0 for improved appearance (right).

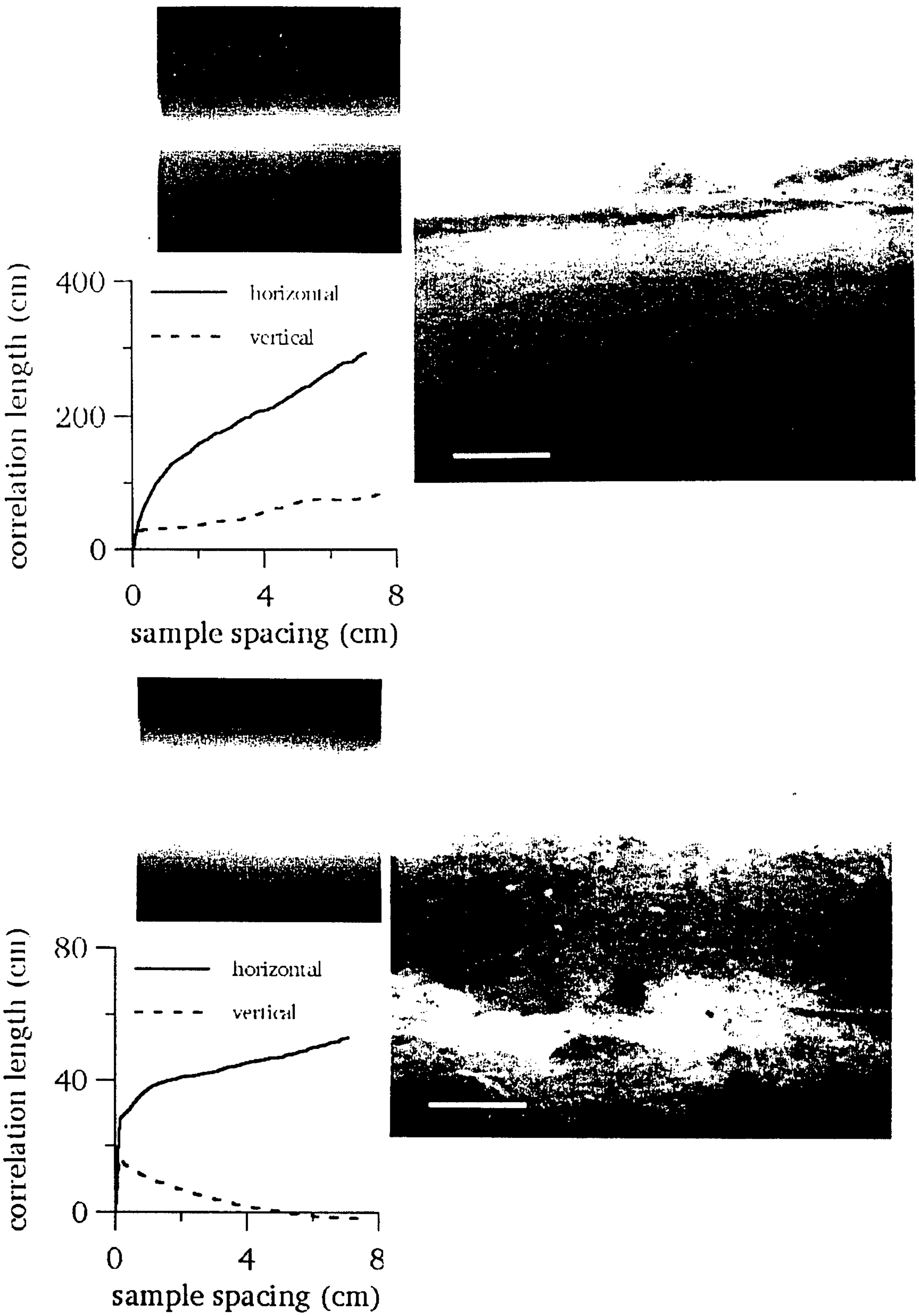

Figure 4: X-radiographs 634 (top) and 662 (bottom) with associated autocorrelation function image and calculated correlation lengths.

3.0 LIST OF CBBLSRP RELATED PUBLICATIONS

JOURNAL ARTICLES

Abegg, F. 1994. Methoden zur Unterschung methanhaltiger mariner Weichsedimente. Meyniana 46, 1-9, Kiel.

Abegg, F and A.L. Anderson. Submitted. The acoustic turbid layer in muddy sediments Eckernförde Bay, Western Baltic Sea: Methane concentration, saturation and bubble characteristics. Marine Geology.

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Brandes, H.G, A.J. Silva, A. Ag, and G.E. Veyera. In press. Consolidation and permeability characteristics of surficial high porosity sediments in Eckernförde Bay. GeoMarine Letters.

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